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VESICULAR DIKES AND SUBAERIAL PILLOW LAVAS OF BORABORA, SOCIETY ISLANDS

J. T. STARK
Northwestern University

ABSTRACT

Borabora, one of the Society Islands, represents the eroded remnants of a once more extensive volcano. Ellipsoidal structures in the lavas extend from sea-level to nearly 2,500 feet elevation. The flows are cut by a series of highly vesicular, vertical dikes, striking radially outward from the old crater. Origin of the structures is interpreted as due to the relatively high gas content of the lavas, their nearness to the central volcanic vent, and the coalescing of gas bubbles to form areas of higher pressures.

INTRODUCTION

The subaqueous origin of pillow or ellipsoidal lavas has been described by many writers[1] and is so well established, despite the few instances of subaerial origin, that ellipsoidal structures in ancient lavas is commonly taken as suggestive of emergence. The writer has recently mapped pillow lavas on the island of Borabora, in the South Pacific Ocean, that extend from sea-level to nearly 2,500 feet elevation and which are clearly of subaerial origin. The field work was done on a three weeks' visit during the summer of 1936 and will form the basis of a more detailed report of the geology of the island now in preparation.

[1] J. Volney Lewis, "Origin of Pillow Lavas," *Bull. Geol. Soc. Amer.*, Vol. XXV (1914), pp. 591–654, gives a summary of the literature and tabulates theories of origin. Cf. E. S. Moore, "Notes on the Origin of Pillow Lavas," *Trans. Roy. Soc. Canada*, Vol. XXIV, sec. 4 (3d ser., 1930), pp. 137–39.

LOCATION AND GENERAL RELATIONS

Borabora (Porapora), one of the Western Group ("Les Iles sous le Vent") of the Society Islands, is crossed by south latitude 16° 30′ and west longitude 151°45′ (Fig. 1). The longest diameter, north to south, is barely 6 miles, and its greatest width, along parallel 16°30′, is 2⅓ miles. Exclusive of the coral reefs, the land mass is less than 10 square miles, consisting of three separate islands, and

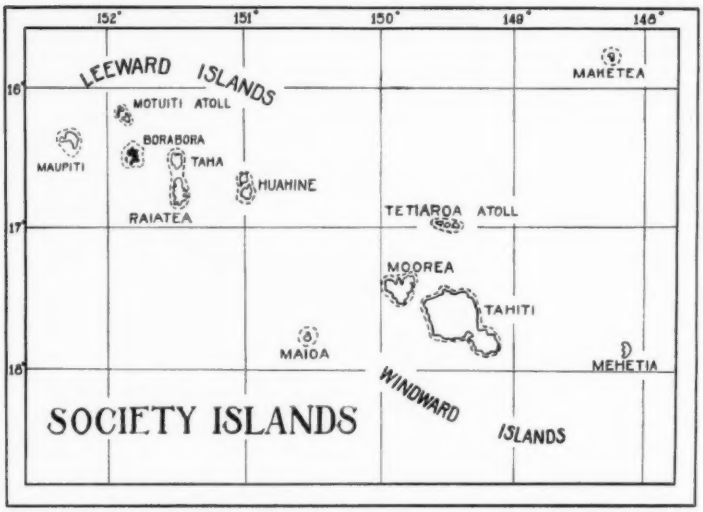

FIG. 1.—Sketch map of the Society Islands

represents the eroded remnants of an old volcano. The eastern half of the cone is preserved in the large island of Borabora, and a small part of the western rim in the two small islands, Tupua (Opua Rahi) and Tupua Iti (Opua Iti). In the central part of Borabora the peaks of Mount Pahia and Mount Temanu reach elevations, respectively, of 2,165 and 2,379 feet (Fig. 2). A continuous ridge descends from Mount Temanu along the entire length of the southern peninsula of Borabora and outlines the southeast rim of the crater. The northern peninsula is also ridgelike in character but is broken by more extensive erosion into several peaks. A low ridge, marking the western rim of the crater, extends the whole length of

Tupua, reaching a maximum elevation in the center of the island of 479 feet (Fig. 3).

A flat of varying width (from an eighth of a mile in the vicinity of Turapuo Bay to a few feet along the northern and eastern shores) partially surrounds the ridges, approximately 6 feet above

FIG. 2.—Outcrop map of Borabora showing the radial arrangement of dikes and quaquaversal dips of the lava flows away from the central lagoon between Borabora and Tupua.

sea-level (Fig. 3). Williams calls attention to similar shore shelves on Tahiti and other islands as indicative of "an actual change in sea level rather than a ubiquitous positive movement of the various islands."[2] Fringing reefs extend from the shores of the three volcanic remnants, and a barrier reef, with many small coral islands, com-

[2] Howell Williams, "Geology of Tahiti, Moorea, and Maiao," *B. P. Bishop Mus. Bull. 105* (1933), p. 23.

pletely surrounds them, except for the small opening in the reef at Teavanui Harbor.

Tropical jungle covers the slopes, and rank vegetation reaches the summits of even the highest peaks. There are, however, many bare,

FIG. 3.—View looking west across the central lagoon; site of the old crater, between Borabora and Tupua. Note marine flat in foreground, approximately 6 feet above sea-level.

FIG. 4.—View looking north across Turapuo Bay toward Mount Pahia (*left*) and Mount Temanu. Note vertical cliffs due to jointing in lava flows.

vertical cliffs (Fig. 4) due to columnar jointing in the lavas, and fresh exposures of volcanic rock are numerous in all parts of the islands.

GEOLOGY

FLOWS

The ridges and peaks are composed of basic lava flows which dip away in all directions from the central lagoon between the southern half of Borabora and Tupua (Fig. 2). In general, the dips average from 3° to 5° with slightly steeper dips in the northern peninsula. Between Popoti and Mataihua peaks, the angles steepen to an average of 12° but decrease quickly as Mount Temanu is approached.

The lava flows range in thickness from 1 to 15 feet. They are commonly less than 4, and average about 6, feet in thickness. This is in contrast to the thicker flows of other islands in the Society group.[3] The lavas vary in structure and texture from coarsely vesicular scoria to aphanitic porphyries, in which small, rounded vesicles are closely spaced throughout. A few of the thicker flows show fine-grained phaneritic textures. In general, a high degree of vesicularity characterizes all and is strikingly developed in many of the flows. Vesicles are so closely crowded that the partitioning walls are of paper thinness. Fresh flow surfaces show rounded, irregular pillow structures, but in none have the forms of typical pahoehoe lavas been developed.

Olivine forms the most abundant phenocrysts in the crystalline aphanites and is present in many of the more glassy, scoriaceous flows. Commonly it is the only megascopic mineral. Pyroxene is the next most abundant phenocryst. In a few of the coarser grained flows, augite and plagioclase are recognized under the hand lens. In many outcrops the lava has been rendered amygdaloidal by calcite fillings, and in a few places bladed and radiating zeolites form conspicuous amygdules.

Fragmental material of explosive origin is conspicuously absent in most parts of the islands. A few small boulders of questionable breccia-agglomerate are strewn along the east shore of Tupua Iti; and highly weathered flows north of Fanui, between Popoti and Mataihua peaks, may possibly represent agglomerate. The lack of ejected material here is striking even for the Society Islands, where fragmental deposits are not common. Beds of breccia and tuff brec-

[3] J. D. Dana, "A Dissected Volcanic Mountain (Tahiti): Some of Its Revelations," *Amer. Jour. Sci.*, Vol. XXXII (3d ser., 1886), p. 251; Williams, *op. cit.*, pp. 31–32.

cia at least 250 feet thick are reported on Tahiti,[4] and a survey of the interior will doubtless reveal much more. The writer has mapped over 1,000 feet of breccia and agglomerate on Moorea.

DIKES

A remarkable series of vertical and nearly vertical dikes cut all exposures of the flows. Dip and strike measurements were made on more than two hundred outcrops, showing one or more dikes, and the number of dikes indicated by loose rubble and in covered areas must total many hundreds more. They strike radially, parallel the dips of the flows, and, like spokes of a wheel, converge toward a central hub situated somewhere in the central lagoon between Bora-bora and Tupua (Figs. 2 and 3). The width of the dikes varies from 4 inches to 10 feet, the great majority averaging from 1 to $2\frac{1}{2}$ feet. Steep dips are characteristic, only a small number departing more than 10° from the vertical. In a few outcrops the dikes are offset a few inches to a few feet by sill-like flats joining the vertical sections. Rarely, thin sheets of igneous rock, varying from 6 inches to 1 foot thick, parallel the vesicular flows and possibly represent sill-like stringers from the dikes.

In the field the dikes may be divided into two general types: (1) olivine porphyries, in which the groundmass varies from aphanitic to finely crystalline basalt, and (2) slightly porphyritic and even textured basalts, in which olivine is not prominent.

The basaltic dikes are much less numerous, more irregular, and in several outcrops intersect the olivine porphyries. More commonly, instead of cutting across the olivine porphyries, they turn at the contact and parallel the older intrusions so that the chilled edges of both dikes are adjacent. A glance at the map (Fig. 2) will show that, although the olivine porphyry dikes strike radially toward a common center, they vary sufficiently in strike directions so that projections of the mapped outcrops would in many cases intersect. But in no place were the olivine porphyries found cutting one another. Many outcrops showed two or more dikes, parallel to each other, their walls in contact, as if a younger intrusion had been turned by the older, as observed in the case of the basaltic dikes.

[4] Williams, *op. cit.*, p. 40.

In one outcrop, on the west slope of Popoti Peak (Fig. 5), four dikes, showing pronounced chilling of their borders and their walls in contact, suggest that there were at least four periods of olivine porphyry intrusion.

Many dikes of both types exhibit vesicular structures. In some the vesicularity extends the entire width of the dikes and is absent only in the chilled margins. In others the vesicles are prominent only in the central portions, occurring in lines parallel to the dike walls. The finer grained dikes, especially the basaltic ones, commonly show thinly ribbed, weathered surfaces formed by differential erosion between beadlike lines of very small vesicles.

FIG. 5.—Four olivine porphyry dikes on northwest slope of Popoti Peak. The dike walls are in contact, and each dike shows chilled borders and columnar jointing.

One such dike, 2 feet wide, contains oval-shaped masses of coarsely vesicular structure, ranging from 5 by 6 to 10 by 12 inches in cross section, surrounded by poorly developed concentric lines of fine vesicles (Fig. 6). Chilled borders of the dike have a dense, nonporphyritic texture. In the vesicular cores the rock is gray with plagioclase laths $\frac{1}{8}$ inch in length. Between the oval areas the texture is aphanitic with no minerals recognizable. But for the general structural relations, which are well exposed in the outcrop, the dike might easily be mistaken for pillow lava.

Owing to the vesicularity, loose fragments of the dikes can scarcely be distinguished from lava flows. In outcrop, however, the structural relations are graphically shown in numerous cliff faces exhibiting hundreds of vertical intrusions cutting gently dipping

lava flows. All but the very thinnest dikes have chilled borders, and characteristic columnar jointing is well developed in nearly every outcrop.

An exception to these two main types of dikes occurs in a 100-foot-wide intrusion which cuts the lava flows on the extreme south end of Tupua. The dike forms a bold ridge, 60 feet high, strikes N. 20 E., and dips vertically. Joint blocks, from 30 to 40 feet in diameter, suggest a rude columnar structure, and the dikelike char-

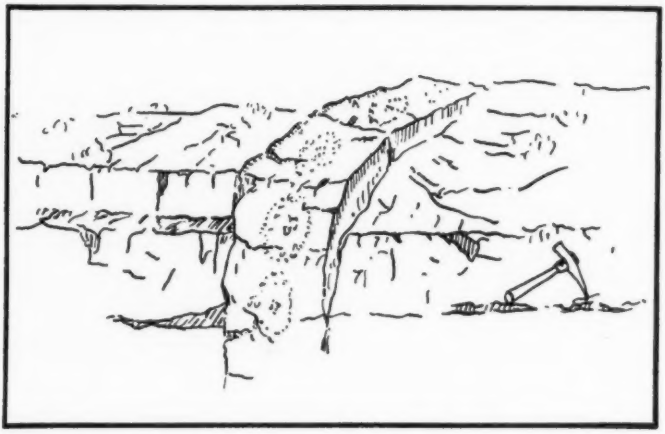

FIG. 6.—Sketch of a basalt dike, southern peninsula of Borabora, showing oval-shaped areas of coarsely vesicular structure surrounded by less vesicular and finer grained rock.

acter is further emphasized in prominent chilling of the margins in contact with the flows. The dike is a coarse-grained olivine diabase throughout most of its width, composed of crystals of augite, from $\frac{3}{8}$ to $\frac{1}{2}$ inch long, in a matrix of slightly less coarse plagioclase and olivine. About 7 feet from the edges, the texture becomes finer grained, grading into an extremely fine-grained aphanite at the flow contact. For at least 50 feet on both sides of the dike, the lava flows have been recrystallized to coarse-grained rock. Covered areas obscure the entire width of the contact metamorphic effects. As no alteration of the lava flows is noticeable adjacent to the smaller dikes, the intensive metamorphism here suggests that the large dike may represent the late filling of an old feeding-vent to the crater.

ELLIPSOIDAL STRUCTURES

In many places around the shores of Borabora, Tupua, and Tupua Iti, fresh surfaces of pillow lavas are exposed. From these outcrops at sea-level to the crests of the ridges and extending to more than a 2,300-foot elevation on the peaks of Mounts Pahia and Temanu, numerous vertical cliffs exhibit excellent exposures of ellipsoidal flows. Alternating with the pillow lavas, but much less abundant, are more or less homogeneously vesicular, non-ellipsoidal flows.

FIG. 7.—Vertical section of ellipsoidal lava, southern peninsula of Borabora, showing a pillow with characteristic concentric lines of vesicles and central hollow due to weathering of more coarsely vesicular core.

The pillows generally occur in a series of thin flows from 1 to 4 feet thick. Many cliffs and connecting ledges permit measurements in several directions. In size the pillows vary from small ellipsoids, 4 and 5 inches in diameter, to large pillows 7 and 8 feet long. An average structure would approximate 1 by $1\frac{1}{2}$ by 2 feet. The long diameter of the pillows nearly always extends in the direction of the dip of the lava flows. A banded, concentric arrangement of vesicles is characteristic (Fig. 7). In the average cross section the outer 2 or 3 inches are extremely vesicular. Commonly the vesicles are elongated, from $\frac{1}{8}$ to $\frac{1}{4}$ inch, and show a radial arrangement around the periphery of the pillow. The outer zone of vesicular lava is succeeded by an intermediate zone of more massive lava in which vesicles may be visible only under the hand lens, or by slight, con-

centric ribbing due to differential erosion between fine lines of small vesicles, as observed in the thinly ribbed, basaltic dikes. This intermediate zone is in turn succeeded by a central core that is highly porous with rounded vesicles, as large and commonly larger than the elongated vesicles of the outer rim. In many exposures the porous centers have been first to weather, forming hollows in the pillows. In the 500- and 1,000-foot cliffs of Mounts Pahia and Temanu (Fig. 4) parallel rows of hollow pillows mark the alternation of ellipsoidal structure with more massive flows. On the north and east sides of these mountains the same flows are exposed in a series of gently dipping ledges with surfaces identical with the exposures of pillow lavas at sea-level. In cross section many of the pillows show flattening on the bottom.

The pillows form the central part of many flows, and a zone of non-ellipsoidal lava forms the upper and lower parts of the flows. The non-ellipsoidal material, ranging in thickness from a few inches to 2 feet, according to the thickness of the flow, is, in general, thicker at the top than at the base of the flow. These relations are sketched in Figure 8. That the lavas were not extremely viscous is indicated by the extreme distortion of pillows in some flows and by sinuous flow lines in lavas capping the ellipsoidal structures.

No evidence was found suggesting the formation of one pillow stemming from a crack in an adjacent pillow, after the manner of "bulbous budding" described by Lewis.[5]

AGE

Williams, in discussing the age of the Tahitian lavas, suggests that migration of volcanic activity in the Society Islands, similar to the general movement established by Hinds[6] for the Hawaiian Islands, has been from west to east. Mehetia, easternmost of the Society Islands, is the youngest volcano. Judging solely on the evidence of erosion, none of the cones of the Society Islands dates farther back than the Pliocene.[7] As Borabora is one of the western-

[5] *Op. cit.*, pp. 646–53.

[6] N. E. A. Hinds, "The Relative Ages of the Hawaiian Landscapes," *Univ. Calif. Publ. Bull. Dept. Geol. Sci.*, Vol. XX, No. 6 (1931), pp. 144–202.

[7] Williams, *op. cit.*, pp. 11–12.

most of the Society Islands and has been eroded to small remnants of its former cone, the age of the lavas might tentatively be placed as late Pliocene or early Pleistocene.

ORIGIN OF THE STRUCTURES

There is no proved uplift in the Society Islands save the relative uplift of approximately 6 feet that is found in all the South Pacific Islands, owing to the recent fall in ocean level.[8] If, as seems likely,

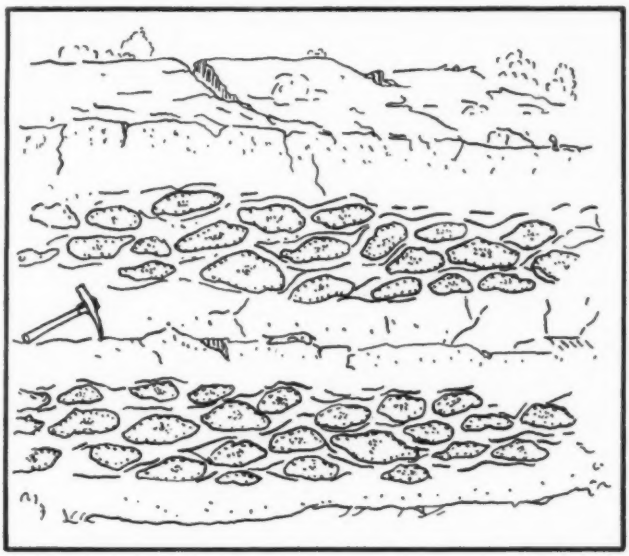

FIG. 8.—Sketch of ellipsoidal lava flows showing flattening of bottom of the pillows and non-ellipsoidal zones above and below the ellipsoidal structures.

the age of the Borabora lavas is Pliocene or younger, there can be no question of their subaerial extrusion. But, assuming no data were available on the age of other islands in the Society group, the abundance of exposures showing fresh surfaces of the lava flows with no evidence of past submergence would be sufficient reason to look elsewhere than to a subaqueous explanation for the origin of the pillow structures.

[8] *Ibid.*, pp. 81–86.

The gentle dips of the flows, the lack of explosive deposits, and the basic composition of the magma give evidence that the lavas were of the less viscous type when extruded. A high gas content is indicated by the extreme vesicularity. Flows 15 feet thick exhibit closely spaced vesicles throughout their entire thickness.

Slower cooling of the interior of the flows, permitting a coalescing of gas bubbles (that seemed unable to escape readily through the more viscous upper and lower parts of the flow), might explain the coarse vesicles commonly found in the center of the flows. Gas pressures in places may have been thus sufficiently increased to cause billowing of the still plastic flow, inaugurating the pillow structures. Some support is given to this by the presence of non-ellipsoidal zones above and below pillow structure in separate flows. For example: a flow extrudes and starts to vesiculate. The top and bottom chill, whereas, in the central parts, crystallization may be slightly more rapid at certain points, which would start vesiculation and give billowing centers. Also certain parts might undercool a bit more than others, and, when they did start to crystallize, the vesiculation would be more rapid. Such action would produce the coarse vesicles at the center of the pillows and thus cause a billowing action. Ellipsoidal form, elongation in the direction of the movement (down dip), and the flattening of the bottom of pillows would be the natural results of the response of such a slowly cooling lava to forces of gravity.

The vesicularity of the dikes is not very different from that of the flows. Vesicles are missing in the chilled zones of some and in all but the central zones of other dikes, whereas, in the lavas, they go all the way from top to bottom of the flows. The presence of bands of vesicles in relatively thin dikes and the phenomenon of vesicularity extending throughout the width of many 4- and 5-foot dikes suggest that the escape of gases was not readily accomplished after the chilling of the margins. This chilling of the edges would cut off the escape of gases into the porous wall rock. The pressure is then dependent upon the hydrostatic head of the magma in the dike, which may not be any greater than that due to the hardened crust of the flows.

The vesiculation of a lava can readily be explained, as pointed out

by Morey,[9] by the concentration and consequent rapid increase of vapor pressure of the dissolved water with advancing crystallization. The order of magnitude of the pressure thus developed is indicated by the experiments of Goranson,[10] who showed that the vapor pressure of a granite melt rose from 140 bars to 1,000 bars as the water was concentrated by crystallization from 1 per cent to 6.5 per cent. If there was only the cooled crust of a lava flow or the hydrostatic head of a dike to act as restraining pressure, that restraining pressure would soon be exceeded as the lava crystallized, and the water would begin to boil out.

The pseudo-pillow structures, occurring in one of the dikes (Fig. 6), may have originated in similar manner to billowing in the flows by coalescing of gas bubbles forming areas of greater pressure. Relative lack of movement after intrusion of the dike would explain the more nearly symmetrical structures. In general, with the intrusions, cooling is more regular and uniform, giving less opportunity for billowing. Vertical strings of bubbles in the dikes are probably due to the rising bubbles in a quiet, and more or less uniformly cooling, intrusion.

SEQUENCE OF EVENTS

The sequence of events in the formation of the pillow lavas and the vesicular dikes is interpreted as follows:

1. The formation of a lava cone by successive, quiet flows of lava, containing a relatively high amount of gas to cause the extreme vesicularity and pillow structures.

2. The subsidence of magma in the central vent and cooling of the porous lavas fairly rapidly to develop radial fissures or joints in the crater walls—vertical planes of weakness that extended for considerable distances out into the lava cone.

3. The resurgence of magma in the crater and the intrusion of porphyry dikes along the radial joint planes.

4. The probable repetition of 2, 3, many times. Instead of cutting the older dikes, the later series are turned at the contact and parallel

[9] G. W. Morey, "The Development of Pressure in Magmas as a Result of Crystallization," *Jour. Washington Acad. Sci.*, Vol. XII (1922), pp. 219–30.

[10] R. W. Goranson, "Some Notes on the Melting of Granite," *Amer. Jour. Sci.*, Vol. XXIII (5th ser., 1932), pp. 227–36.

the walls of the earlier intrusions. At least four periods of olivine porphyry intrusion are suggested by the four dikes (Fig. 5) with their chilled margins in contact.

5. The intrusion of the nonporphyritic, basaltic dikes, less extensively and with more irregular trends than the olivine porphyries, and in a few places cutting across the older intrusions.

ACKNOWLEDGMENTS.—Acknowledgments are gratefully made to Professor Carl M. Beecher, who first interested the writer in the geology of Borabora, and in whose company the trip was made; to Matahi, whose hospitality and intimate knowledge of the island aided materially in planning the work; to Tarahea, an enthusiastic guide and field assistant; and to Dr. A. L. Howland, of Northwestern University, for help in the preparation of the manuscript.

OPENING OF THE PLEISTOCENE IN THE ROCKY MOUNTAINS OF THE UNITED STATES

WALLACE W. ATWOOD AND WALLACE W. ATWOOD, JR.
Clark University

ABSTRACT

Glacial till of early Pleistocene age has been discovered in various sections of the Rocky Mountain region. The distribution and topographic relations of these ancient deposits indicate that the early glaciers existed before the modern valleys and canyons were developed. Ice formed in mountains which have been greatly modified or completely removed during subsequent time. The widely scattered remnants of early drift record the most extensive development of ice in the mountains and mark the opening of the Pleistocene in the Rocky Mountain region.

The oldest glacial drift of Pleistocene age thus far reported from the Rocky Mountain region in Colorado is called the Cerro till. It was discovered west of Tongue Mesa at the northern margin of the San Juan Mountain area in 1883[1] and later at many other localities (Fig. 1, Loc. 1, 2, 3).[2] The known distribution of this formation in southwest Colorado is shown on the map of glacial features accompanying a paper dealing with the physiographic history of that region.[3] At Cerro Summit, on the narrow-gauge road of the Denver and Rio Grande Railway, just west of the Black Canyon of the Gunnison and a few miles east of Montrose, a large amount of this old glacial deposit mantles the hilltops and the stream divide. At this, the type locality, the deposit shows all the usual characteristics of glacial drift. There is physical and lithological heterogeneity, no assortment of material, striated stones, and a morainic topography. There are numerous boulders, some 15–20 feet in diameter, in the glacial material.

At Horsefly Peak the Cerro till mantles an area of 4 or 5 square

[1] R. C. Hills, "Extinct Glaciers of the San Juan Mountains, Colorado," *Amer. Jour. Sci.*, Vol. XXVII (1884), pp. 391–96; *Colorado Sci. Soc. Proc.*, Vol. I (1883), pp. 39–46.

[2] W. W. Atwood and K. F. Mather, "The Evidence of Three Distinct Glacial Epochs in the Pleistocene History of the San Juan Mountains, Colorado," *Jour. Geol.*, Vol. XX (1912), pp. 385–409.

[3] W. W. Atwood and K. F. Mather, "Physiography and Quaternary Geology of the San Juan Mountains, Colorado," *U.S. Geol. Surv., Prof. Paper 166* (1932), pp. 101–13 and Pl. 3.

miles and adds several hundred feet to the height of the mountain. At that locality there are masses of rock from 20 to 25 feet in diameter (Fig. 2). Here and at Cerro Summit the huge boulders have

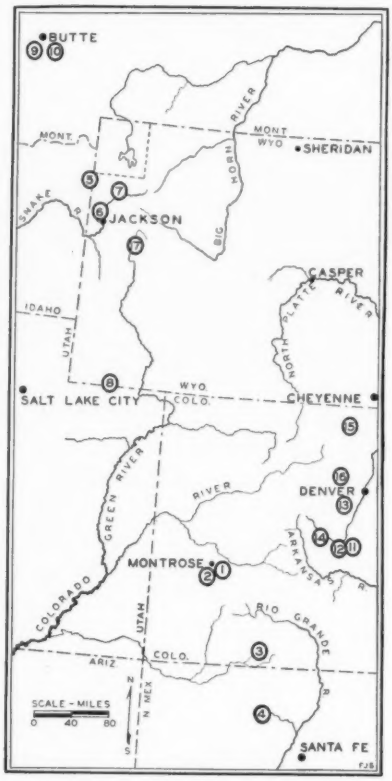

FIG. 1.—Index map showing the location of early Pleistocene glacial deposits referred to in this article. *1*, Cerro Summit; *2*, Horsefly Peak; *3*, near Pagosa Springs; *4*, Canjilon Divide; *5*, southwest corner of Yellowstone National Park; *6*, Jackson Hole, near Jackson; *7*, Jackson Hole, near Moran; *8*, north slope, Uinta Range; *9*, Silver Bow; *10*, Grace; *11*, Divide, northwest of Pike's Peak; *12*, southwest of Florissant; *13*, northeast of Bailey; *14*, in South Park; *15*, near the canyon of the Cache la Poudre; *16*, near Nederland; *17*, Upper Green River Valley.

come from a scoriaceous latite of middle or late Tertiary age that no longer mantles the San Juan region. The boulders must have

been formed at a time when the mountains were much higher, and certainly at a time preceding the development of the modern canyons in the range (Fig. 3).

FIG. 2.—Early Pleistocene glacial drift on the summit of Horsefly Peak, Ouray County, Colorado (Loc. 2). The large boulders in this deposit were derived from a Tertiary latite which once covered large areas in this section but has since been removed from all except a few high summits.

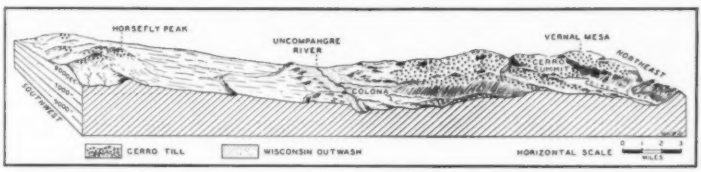

FIG. 3.—A sectional block drawing from Vernal Mesa to Horsefly Peak across the valley of Uncompahgre River, Montrose Quadrangle, Colorado (Locs. 1 and 2). The position of Cerro till on and near the high divides between present drainage lines indicates the amount of erosion that has occurred in the region since early Pleistocene. Broad valleys and deep canyons now intervene between the mountains and the isolated hills capped with Cerro drift. A few miles upstream from Colona, moraines of the Durango and Wisconsin stages rest on the floor of the modern valley. Outwash from the Wisconsin glaciers appears in the present Uncompahgre Valley, 2,000–4,000 feet below the Cerro deposits.

More recently very old Pleistocene drift has been reported at Canjilon Divide[4] in the mountains of New Mexico southeast of the

[4] H. T. U. Smith, "Periglacial Landslide Topography of Canjilon Divide, Rio Arriba County, New Mexico," *Jour. Geol.*, Vol. XLIV (1936), pp. 836–60.

San Juan area and correlated in age with the Cerro till (Fig. 1, Loc. 4). West of the Teton Range[5] and in Yellowstone National Park early Pleistocene drift has been discovered and described as the Buffalo till (Fig. 1, Loc. 5). In the Jackson Hole region[6] east of the Teton Mountains similar deposits have been found at several localities (Fig. 1, Loc. 6, 7). These are believed to be of about the same age as the Buffalo till. Within the last few years early Pleistocene drift has been reported at the north margin of the Uinta Mountains (Fig. 1, Loc. 8).[7]

In the vicinity of Butte, Montana, there are remnants of a very old glacial drift which were interpreted by the senior author, in 1915, to be possibly of Cerro age.[8] A re-examination of these deposits during the past season by the present authors has removed all doubt as to the accuracy of the earlier age determination. One of the Butte localities extends from 2 to 5 miles south of Silver Bow (Fig. 1, Loc. 9). Here there is a very heavy bouldery formation with a hilly topography (Fig. 4). This deposit is at the east margin of a broad, intermontane trough which was not glaciated during the later stages of the Pleistocene. It is not related to any valley or canyon of the modern topography; it is so located that it could not have come from the modern catchment basins in the nearest mountain area of today. This deposit contains many boulders 8–10 feet in diameter and some that range up to 20 feet in diameter. In this respect the deposit checks very well with those at the discovery locality on Horsefly Peak and at Cerro Summit, the type locality, north of the San Juan Range.

One and a half miles north of the little railroad station at Grace, Montana, which is southeast from Butte, there are exposed along the newly built highway several sections in an ancient till that is far removed from and unrelated to the modern canyons or modern

[5] E. Blackwelder, "Post-Cretaceous History of the Mountains of Central Western Wyoming," *Jour. Geol.*, Vol. XXIII (1915), pp. 328–33.

[6] F. M. Fryxell "Glacial Features of Jackson Hole, Wyoming," *Augustana Library Publ. No. 13* (1930), pp. 26–35.

[7] W. H. Bradley, "Geomorphology of the North Flank of the Uinta Mountains," *U.S. Geol. Surv., Prof. Paper 185* (1936), pp. 194–95.

[8] W. W. Atwood, "The Physiographic Conditions at Butte, Montana, and Bingham Canyon, Utah, When the Copper Ores in These Districts Were Enriched," *Econ. Geol.*, Vol. XI (1916), pp. 717–19.

cirques (Fig. 1, Loc. 10). At this locality all the physical characteristics of glacial drift are displayed and striated stones are abundant (Fig. 5).

FIG. 4.—Massive morainic hills 4 miles south of Silver Bow, Montana (Loc. 9). These drift deposits are unrelated to the moraines of middle or late Pleistocene time and are, therefore, assigned to the earliest Pleistocene glaciers. Long exposure to weathering and erosion has removed all traces of glacial striae on the surface boulders and softened the topography.

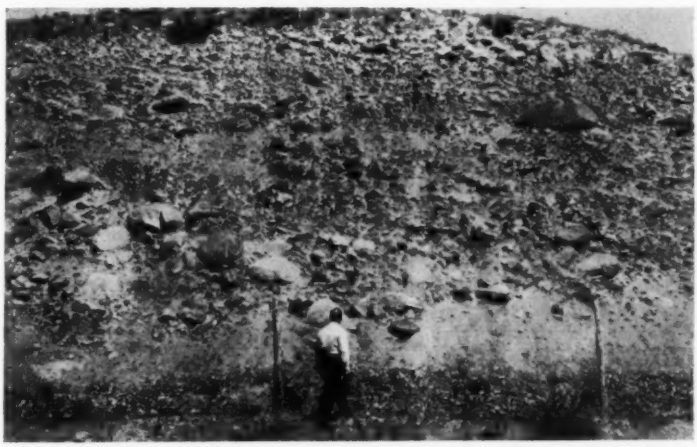

FIG. 5.—A recent road cut north of Grace, Montana, produced this excellent exposure of early Pleistocene drift (Loc. 10). The presence of glacial material was not reflected in the present topography. Numerous well-striated stones were found in the less-weathered portions of this drift.

In 1915 the senior author found other remnants of bouldery deposits on the highlands northeast of Butte. These were not revisited in 1936, but they are now believed to be of Cerro age. At the two best localities, the one south of Silver Bow and the one near Grace, the old glacial deposits rest upon eroded surfaces in the Bozeman beds which have been judged to be of Oligocene or Miocene age. This evidence makes it clear that the Butte deposits do not correspond in age to the Eocene till found near Ridgway, Colorado.

The exact geologic age of the Cerro-Buffalo glacial deposits cannot be definitely determined, but it seems reasonable from studies made at various localities in the Rocky Mountain region to believe that they mark the opening of the Pleistocene. They contain at certain localities boulders of middle or late Tertiary lavas. They were not laid down until after a Pliocene peneplain in the mountain province was uplifted and somewhat dissected. Although at the surface at all known localities, they are much older than the conspicuous deposits left by alpine glaciers of two later stages and reported as present in nearly every range in the Rocky Mountains of the United States and Canada.

The characteristics of these very old Pleistocene till deposits may be summarized as follows:

1. They are not associated with the modern valleys and canyons and clearly antedate their development.

2. They are all on surfaces that are a part of or below the Pliocene peneplain, which is the one widespread, old-age erosion surface in the Rocky Mountain region.

3. They came from mountain ranges that later have been greatly modified or entirely removed.

4. They record the most extensive development of ice in the mountains during the Pleistocene.

5. They are commonly so much eroded that they have lost their original morainic topography and are inconspicuous relief features in the present erosional landscape.

6. They are located at the surface and in all cases are deeply weathered.

7. At several localities they contain huge boulders.

During the past four seasons several additional remnants of this very old Pleistocene till have been found, by the present authors, at widely separated localities. Near Divide, northwest of Pike's Peak, there are four or five exposures of an ancient till containing striated stones (Fig. 6). These deposits are located on high ridges between modern stream valleys cut a little below the Rocky Mountain peneplain horizon. They are definitely not related to the modern glaciated canyons on the slopes of Pike's Peak and they are far beyond the points reached by late Pleistocene ice (Fig. 1, Loc. 11).

FIG. 6.—Severely weathered glacial till in the vicinity of Divide, northwest of Pike's Peak, Colorado (Loc. 11). Situated on high divides between the modern streams and far removed from valleys which were glaciated during late Pleistocene time, these ancient drift deposits are unquestionably related to a very early glaciation. No glacial topography now exists and striated stones are very rare.

About 10 miles southwest of Florissant, in a wilderness region crossed by a few old roads, another occurrence of ancient drift was discovered (Fig. 1, Loc. 12). Here the glacial deposits are far removed from the present mountains, not related to the valleys or canyons of today in any genetic sense, and situated on high stream divides.

Near the main highway (U.S. Route 285), 8 miles northeast of Bailey, Colorado, remnants of an ancient till were found which are interpreted to be of Cerro age (Fig. 1, Loc. 13). At this locality

the old drift is not related to the glacial deposits in the modern valleys or canyons. It is older than the canyon-cutting stage of erosion.

In South Park there is a bouldery ridge, several miles in length, which extends through the middle section of the park (Fig. 1, Loc. 14). This ridge is far away from all high mountains and not in any way related to modern canyons or glaciated valleys. Here the boulders range up to 10 feet in diameter and are so abundant and so conspicuous that their glacial origin is strongly suggested. The material is largely granitic and that which has rested on the surface for thousands of years does not carry striae. However, the authors have found it impossible, at many localities, to find any striated stones in granitic drift of Wisconsin age.

In the Home Quadrangle of northern Colorado, a few miles north of Estes Park, we found, on the high divide north of the Canyon of the Cache la Poudre, a mass of bouldery material which we believe to be of glacial origin (Fig. 1, Loc. 15). If so, it is certainly of Cerro age. It is on a surface a little below Green Ridge which is interpreted as one of the excellent remnants of the one widespread peneplain in the Rocky Mountain region.

Van Tuyl and Lovering have reported material in the vicinity of Nederland, Colorado, which they have thought at times might be of glacial origin.[9] This material is on a high divide far away from the glacial deposits associated with the modern valleys and canyons and extends as a prominent ridge for several miles (Fig. 1, Loc. 16). This deposit was visited by the authors during the 1936 field season. Glacial striae were found on some of the stones, and in nature, composition, and topographic relations this deposit seems to be undoubtedly of Cerro age.

Kirkendall,[10] in his field studies at the northwest end of the Wind River Range, has found drift of a very old glacier which he has interpreted to be comparable in age to the Buffalo of Fryxell and

[9] F. M. Van Tuyl and T. S. Lovering, "Physiographic Development of the Front Range," *Bull. Geol. Soc. Amer.*, Vol. XLVI (1935), p. 1312.

[10] W. E. Kirkendall, "The Glacial Features of the Upper Green River Valley, Wyoming," *Clark University Theses Abstracts* (1935), pp. 97–100.

Blackwelder (Fig. 1, Loc. 17). These deposits were first reported by Blackwelder in 1915.[11]

It was anticipated when the discovery of very early Pleistocene drift was made in the San Juan region that many other remnants of this ancient till would be found. It is surprising that more have not been reported by field workers in the high mountain regions near the Pacific coast.

The distribution and topographic relations of the glacial deposits referred to in this paper indicate that the Cerro-Buffalo ice formed in high mountains which existed early in the Pleistocene. It was after the uplift which raised and deformed the late Tertiary cycle-end-surface that snows accumulated and early Pleistocene glaciers came into existence. Some of the new-cycle dissection had taken place before the ice descended from the mountains. The distribution and topographic relations of these deposits of drift indicate, furthermore, that there has been a renewal of mountain growth during the Pleistocene, which accounts for a later rejuvenation of streams, a great deepening of valleys, the excavation of huge canyons, the removal of vast quantities of alluvial material from intermontane basins, the resurrection of certain mountains that were buried during mid-Tertiary time, and the re-emphasis of the crest-line peaks of the larger mountain ranges. All this occurred since the Cerro-Buffalo moraines were deposited. In view of the great antiquity of these glacial formations they have been correlated tentatively with the oldest moraines recognized in the upper Mississippi valley.

The later history of erosion in the mountain region may be subdivided into various minor stages, but it is not the purpose of this article to set forth that phase of our work. The Cerro-Buffalo drift is believed to represent the first ice work of the Pleistocene and its topographic relations make it possible to reconstruct, in imagination, the landscape at the opening of the last great ice age in the Rocky Mountain region.

[11] E. Blackwelder, "Post-Cretaceous History of the Mountains of Central Western Wyoming," *Jour. Geol.*, Vol. XXIII (1915), pp. 331–32.

THE TOM SAUK LIMESTONE MEMBER OF THE BONNETERRE FORMATION IN MISSOURI

GEORGE F. BRIGHTMAN
University of Minnesota

ABSTRACT

The Tom Sauk member of the Bonneterre formation is a pure, fine-grained, sublithographic limestone, which occurs in that formation only in the St. Francois Mountains of Missouri. The limestone is irregular in distribution, thickness, and stratigraphic position, and peculiar in lithology. The writer suggests that it is a chemical deposit precipitated in closed basins among the hills of igneous rock. The waters in these basins were fresh or brackish, and the sediment there escaped the dolomitization by sea water which the Bonneterre dolomite suffered. Thin sections of the limestone show certain textures suggesting that the original sediment was similar to the finely divided lime muds now accumulating in parts of the Bahamas.

INTRODUCTION

References to a limestone or "marble" in the Bonneterre formation are found in a number of reports of the Missouri Geological Survey, ranging in date from 1855 to 1895. They are, however, little more than lists of localities and remarks on economic possibilities. In 1923, during the mapping of the Potosi quadrangle, Dake rediscovered what he called the "marble phase of the Bonneterre." In his report,[1] published in 1930, was included a fairly complete bibliography of the earlier references, and a partial list of Tom Sauk localities. Dake established that the "marble" was a member of the Bonneterre formation but did not discuss the question of origin.

Since 1930 the Missouri Geological Survey has recognized the "marble" in a number of well cuttings and in unpublished well logs has called it the Tom Sauk.[2] The author has adopted this term and proposes as a type locality the outcrop on the south side of Little Tom Sauk Creek, on the boundary between Iron and Reynolds counties, Missouri.

The present paper describes the Tom Sauk member, which is unusual both in lithology and in distribution, and offers a hypothesis of origin to explain these peculiarities.

[1] C. L. Dake, "Geology of the Potosi and Edgehill Quadrangles," *Mo. Bur. Geol. and Mines*, Vol. XXIII (2d ser., 1930), pp. 62–78.

[2] H. S. McQueen, personal communication.

REGIONAL SETTING

Since the Tom Sauk member outcrops only in the St. Francois Mountains and is not found elsewhere in Missouri, a consideration of the geology of this region is necessary. The St. Francois Mountains are a physiographic subdivision of the Ozark plateaus. The area, roughly circular and approximately 40 miles in diameter, lies about 90 miles south of St. Louis and some 40 miles west of the Mississippi River. It is distinguished from the surrounding Salem Plateau by greater relief due to the presence of hills of resistant igneous rock among the softer sedimentary formations. The igneous rocks are of a variety of types, the most important of which are the granites and granite porphyries and the rhyolites and rhyolite porphyries. The latter, together with other associated extrusive rocks, are often grouped together under the common name of felsites.

The intrusive and extrusive igneous activity which formed these rocks is all of pre-Cambrian age and long preceded the deposition of the Cambrian sediments. In near-by St. Francois and Ste. Genevieve counties there are dikes of post-Cambrian age,[3] but there is as yet no evidence of such activity within the St. Francois Mountains or in the area of Tom Sauk outcrop.

The igneous rocks form the numerous hills or "knobs" which characterize the St. Francois region. These rise 500–1,000 feet above the valley bottoms and have elevations of 1,200–1,800 feet. Occasionally these knobs form short ridges, but generally they stand either alone or in groups of two or three. Sedimentary rocks occupy many of the valleys between the igneous hills. In most cases the sediments lap up considerably on the hills and in some instances completely cover them. The occurrence of such buried knobs indicates that the present mountains are largely not the result of the present erosion cycle. Instead the hills were carved out of the igneous land mass in pre-Cambrian time and later buried beneath the sediments which are now being removed. Drill records of the thickness of

[3] W. H. Tarr and W. D. Keller, "Post-Devonian Igneous Intrusion in Southeastern Missouri," *Jour. Geol.*, Vol. XLI (1933), pp. 815–23; G. W. Rust, "Preliminary Notes on Explosive Volcanism in Southeastern Missouri," *Jour. Geol.*, Vol. XLV (1937), pp. 48–75.

sediments remaining in the valleys indicate that the average relief of the pre-Cambrian surface was about 1,500 feet. In places it was as much as 2,000 feet.[4]

The lower part of the sedimentary rock column of the St. Francois area is given in Table 1. There was apparently no break in deposition from Lamotte through Derby-Doerun time, but the char-

TABLE 1

Era	Period	Epoch	Formation and Thickness	Character
			Important unconformity	
Paleozoic	Cambrian	Saratogan or St. Croixian	Derby-Doerun 0′–110′	Light gray to buff, finely crystalline to earthy dolomite. Noncherty
			Davis 0′–225′	Gray or greenish shale, thin-bedded to massive limestone, and limestone conglomerate. Noncherty
			Bonneterre 0′–470′	Massive gray to buff crystalline dolomite, with Tom Sauk member of fine-grained, sublithographic limestone at varying horizons. Noncherty. Near base often contains numerous pebbles of igneous rock
			Lamotte 0′–260′	White to brown cross-bedded or massive sandstone with some shaly layers. Noncherty. Near base often becomes arkosic conglomerate of igneous pebbles
			Important unconformity	
Proterozoic	Algonkian(?)			Felsites, granite, and granite porphyry, intruded by basic dikes and masses

acter of the sediment and probably the depth of the sea varied considerably. The Lamotte sandstone formation occurs chiefly around the edge of the knob region, and in the center of the St. Francois Mountains it is found only in the deepest valleys and basins. Its prominent cross-bedding indicates a shallow-water origin. The sand itself, which is clean and well sorted, was probably largely derived from outside the region. The overlying Bonneterre dolomite is considerably thicker than the Lamotte and occurs in even the highest

[4] C. L. Dake and Josiah Bridge, "Buried and Resurrected Hills of the Central Ozarks," *Bull. Amer. Assoc. Petrol. Geol.*, Vol. XVI (1932), p. 630.

basins in the very center of the knob area. After its deposition the sea again became shallower, for the Davis and Derby-Doerun limestones are largely found around the edges of the igneous area and show intraformational conglomerates and other evidences of shallow-water origin.

The sedimentary formations all show close adjustment in structure to the buried topography. Around nearly every partially buried knob the sedimentary rocks show quaquaversal dips, in places amounting to as much as 10° or 20°. These dips are presumably due to initial slope of the sediment. They naturally decrease as a greater thickness of material is deposited, which makes it possible for any horizon of these formations to rest on the igneous basement. At such contacts there is practically always a certain amount of "basal" conglomerate containing pebbles of the igneous rocks. Such conglomerate, which may be only a few inches or many feet in thickness, may thus occur at any horizon in the several formations.

After Derby-Doerun time there was a considerable erosion period, followed by the deposition of a number of Cambrian and Ordovician formations which eventually overtopped completely the igneous peaks. From this time on, there is no record of any extensive marine invasion of the St. Francois area. Late in the Tertiary the area was reduced to a peneplain, remnants of which are still to be seen in the accordant summit level of the hills. A gradual uplift caused a quickening of stream erosion which stripped off most of the covering of sediments from the buried hills and exposed the old pre-Cambrian valleys with their filling of Cambrian sediments.

DISTRIBUTION

The distribution of the Tom Sauk outcrops and of the occurrences in deep-drill holes are shown in Figure 1. The map shows the entire area of igneous outcrops known as the St. Francois Mountains. It will at once be observed that the Tom Sauk outcrops are confined to the immediate vicinity of the exposed igneous rock. As would be expected, the drill-hole localities are grouped more around the edges of the knob area, where the Bonneterre formation is more deeply buried, but even in drill holes the Tom Sauk does not occur outside the boundaries of the St. Francois Mountains. This limited occur-

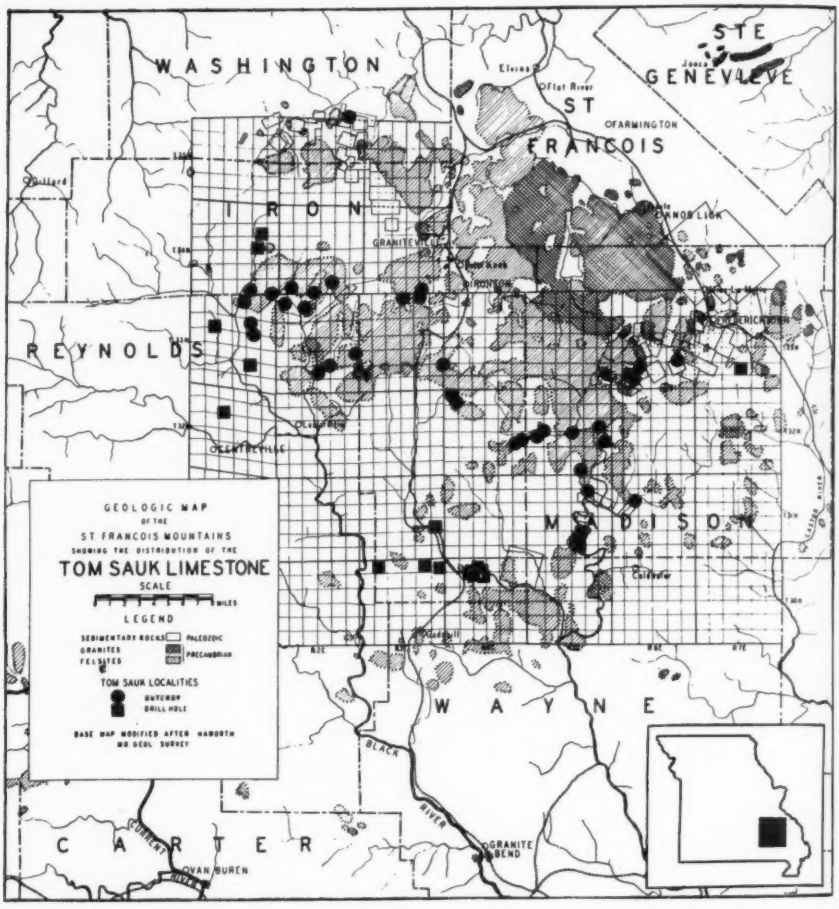

FIG. 1.—Geologic map of the St. Francois Mountains, showing distribution of the Tom Sauk limestone. Inset: Index map of Missouri showing location of the area.

rence is striking in view of the fact that the Lamotte and Bonneterre formations are found in deep drillings to underlie most of Missouri.

Within its sharply limited area of occurrence, the distribution of the Tom Sauk is also somewhat peculiar. On the distribution map (Fig. 1) there are shown thirty-six outcrop localities. All of these have been recently visited by the author or by Dake[5] and his assistants. Most of them were known to early geologists of the Missouri survey, although rarely correctly located. In view of this fact, and of the author's own fairly extensive searches, it seems likely that most if not all of the outcrops have been discovered. Yet the distribution is extremely patchy and discontinuous, much more so than that of the Lamotte or Bonneterre. Not only does the Tom Sauk appear to be confined to a few of the sediment-filled valleys but even between outcrops in the same valley it is impossible to trace any connection. Moreover, the exposures are all small areally; only two are large enough to be shown on the distribution map (Fig. 1) by other than conventional symbols.

This erratic distribution cannot be entirely ascribed to irregularities of the present land form, since deep drillings show that similar conditions exist beneath the surface. In the very extensive collection of well logs in the files of the Missouri Geological Survey there are records of but twenty wells in which Tom Sauk was found. This is a very small percentage of the total number of deep drillings. In the cases where a group of drill holes outlined the shape of a Tom Sauk occurrence beneath the surface, the limestone lens varied from $\frac{1}{2}$ mile or less to 2 miles in diameter. Moreover, practically none of this irregularity can be due to the erosion indicated by the post-Doerun unconformity, since in practically every drill hole Bonneterre dolomite overlies the Tom Sauk. Thus the two anomalies of distribution shown on the outcrop—the occurrence only in the igneous-knob area and the irregular distribution of the exposures—are also found beneath the surface.

THICKNESS

As might be expected from the spotty occurrence of the limestone, its thickness is quite irregular. The maximum thickness observed

[5] *Op. cit.*

on the outcrop was 30 feet. In the drill holes the thickness recorded for the Tom Sauk ranges from 10 to 225 feet, but in the majority it is in the neighborhood of 40 or 50 feet. The thickness often changes considerably in rather short horizontal distances. In the quarter of a mile between two of the holes the thickness drops from 210 feet to 160 feet, and $\frac{1}{2}$ mile distant a third deep well found only 60 feet of Tom Sauk. There are numerous instances of 40 or 50 feet of the limestone pinching out entirely in half a mile or less.

RELATION TO THE BONNETERRE FORMATION

Before the publication of Dake's report[6] the stratigraphic position of the Tom Sauk was unknown. This was due largely to the absence of drill records, since the relations shown on the surface are very puzzling. The Tom Sauk nowhere outcrops above undoubted Lamotte and normally rests directly on the igneous rock, or on "basal" conglomerate. At three localities only there are small thicknesses of dolomite beneath the limestone, but there is no doubt that the Tom Sauk underlies the bulk of the Bonneterre. Consequently there persisted for some time a feeling that the Tom Sauk might be a phase of the Lamotte or even a pre-Lamotte formation. Eventually, however, a drill hole disclosed the Tom Sauk interbedded with basal Bonneterre and overlying the Lamotte sandstone.[7] Since the publication of Dake's report a number of other drillings have disclosed Lamotte below the Tom Sauk. From the several outcrops and drill holes which show Bonneterre below or interbedded with the limestone, there seems no doubt that the Tom Sauk is a member or phase of the Bonneterre.

At several points, however, a sandy conglomerate containing felsite and limestone pebbles intervenes between the Tom Sauk and the overlying Bonneterre. More common is the presence of felsite fragments in the limestone or dolomite at the contact, and several outcrops show pebbles of limestone in the Tom Sauk. These, together with the variable thickness of the limestone might be interpreted as evidence of a general emergence and erosion following the deposition of the Tom Sauk. The author believes, however, that the limestone pebbles are due to submarine erosion and that the influx

[6] *Ibid.* [7] *Ibid.*, p. 77.

of detrital material at the contact is due to changes in current and wave action brought about, probably, by changes in depth of the seas or in the topography of the sea floor. This is reasonable in the light of the archipelago-like character of the region. A further significant point is the variable position of the Tom Sauk member within the Bonneterre. The thickness of Bonneterre between the Tom Sauk and the Davis formation varies from as little as 20 feet to as much as 200 feet.[8] Since the drill records show that there is almost certainly only one horizon of the limestone, it follows that the member occurs at any level in the Bonneterre and is not all strictly contemporaneous. This is a further argument in favor of local submarine origin of the conglomerates at the contact. It also indicates that the physical conditions causing the deposition of the Tom Sauk instead of dolomite occurred not simultaneously over the entire region but locally at different times and, as the variable thickness shows, for different lengths of time.

LITHOLOGY

In lithology, as in occurrence, the Tom Sauk is strikingly different from the Bonneterre formation of which it is a member. The very fact that it is a limestone is an anomaly in this region where the characteristic carbonate rocks are dolomites. It is further set apart by its fine grain, purity, and in places brilliant and variegated colors.

The typical Tom Sauk limestone is light gray or white in color and so fine grained as to appear dull on a broken surface, like lithographic stone. It has a well-developed conchoidal fracture and an almost chertlike appearance (Fig. 2). The dense gray limestone is very commonly cut by irregular veinlets and patches of coarser grained, clear, secondary calcite. Thin wavy discontinuous veinlets of green clay occur in many of the specimens, and some of these clay veinlets contain coarse brown dolomite crystals, obviously secondary.

Many of the limestone varieties differ from the normal type only in color. There is a continuous variation from the very light-gray limestone through the faintest flesh-pink colors to deep reds and

[8] *Ibid.*, p. 75.

browns. Other variations from the normal are dark grays with a faint purple tinge, light-greenish grays, and dark-purple browns. The colored beds of the Tom Sauk are frequently mottled or variegated. Irregular patches of light-pink color, 2 or 3 cm. in diameter fade into a light-gray background. Another common combination is dark-pink and dark-gray green (see Fig. 3). The colored limestones contain the same clay and coarse calcite veinlets as the light-gray Tom Sauk, and some show in addition veinlets of dark-red clay.

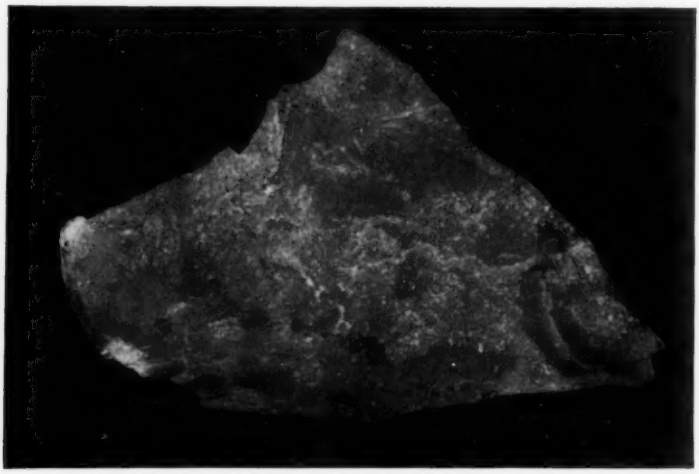

FIG. 2.—Hand specimen of the light-gray, sublithographic variety of the Tom Sauk limestone, showing well developed conchoidal fracture. ×¾.

Angular and rounded fragments of felsite sometimes occur in the colored Tom Sauk. There is a rough correlation between depth of color and amount of felsite present. In the pink and light-red varieties there are occasional small fragments of the igneous rock, 2 or 3 mm. in diameter. In some few beds of the dark-red limestone, felsite occurs in angular fragments over a centimeter in diameter and makes up the bulk of the rock. Curiously enough, the enclosing dark-red limestone is usually identical in color with the felsite fragments, so that the detrital material shows up only on weathering.

On many of the outcrops the limestone is strikingly fresh in ap-

pearance, but in some cases the weathered beds develop what is known as a "pseudo-conglomeratic" appearance (see Fig. 4). The rock apparently consists of irregular rounded or angular nodules of the dense gray limestone enclosed in a matrix of clayey material. The nodules are commonly about 3 cm. in diameter and stand out in strong relief on the weathered surface (see Figs. 5 and 6). The rock is not a conglomerate, however, since the "pebbles" are connected by necks of limestone, and the clay "matrix" is discontinuous. The

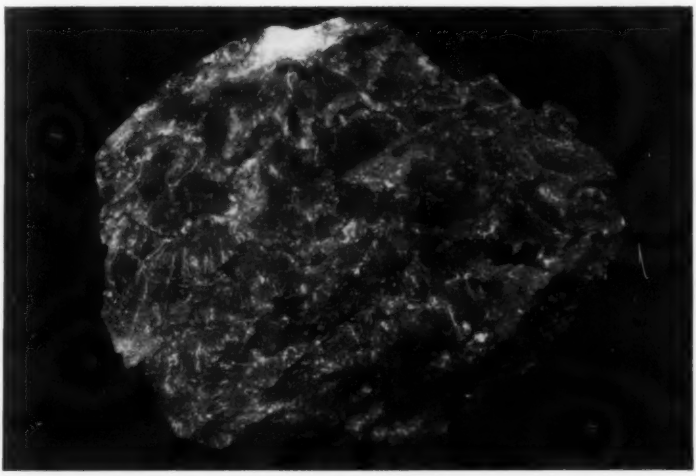

FIG. 3.—Mottled-green and dark-pink fine-grained Tom Sauk limestone. $\times\frac{4}{5}$

pseudo-conglomeratic material frequently grades into unaltered dense limestone within a few inches vertically. The brecciated appearance is apparently due to solution of the limestone by underground water and subsequent filling of the cavities by clay, probably the insoluble residue from the solution of overlying beds.

It is significant to note that there is no systematic vertical arrangement of any of the lithologic varieties. Correlation on a basis of lithologic character proved to be impossible even between outcrops not far apart, which is further evidence of localized and discontinuous deposition.

The purity of the Tom Sauk is demonstrated by the very small

amounts of insoluble residue obtained on digestion of samples in hydrochloric acid. The white and light-colored varieties contain but 1 or 2 per cent of insoluble material, and the darker colored varieties but 3 or 4 per cent. Only a few specimens, in which large numbers of felsite fragments were visible to the naked eye, exceeded these figures. In one of these, however, the felsite pebbles of a centimeter or more in diameter, made up no less than 75 per cent of the rock.

FIG. 4.—Exposure of Tom Sauk limestone underlying Bonneterre dolomite. Hammer at the contact. Note nodular weathering of the limestone.

The normal small residues are made up almost entirely of thin flakes of grayish-green clay, derived probably from clay veinlets in the limestone. This has been identified as the mineral beidellite. In some of the colored specimens of the limestone there are also chips and irregular masses of a dark-red clay, identified as nontronite. Both types of clay occasionally show the rhombohedral molds known as dolocasts. Some of these are probably molds of the dolomite crystals occasionally found in the clay veins; others

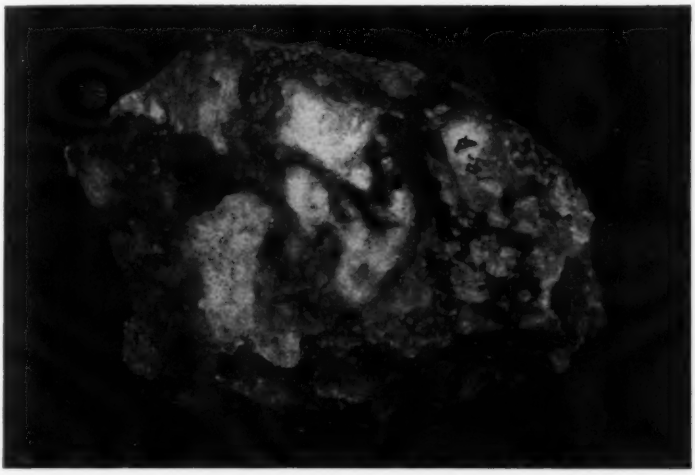

FIG. 5.—Pseudo-conglomerate Tom Sauk. A freshly broken surface, showing red clay seams and dolomite crystals. ×½.

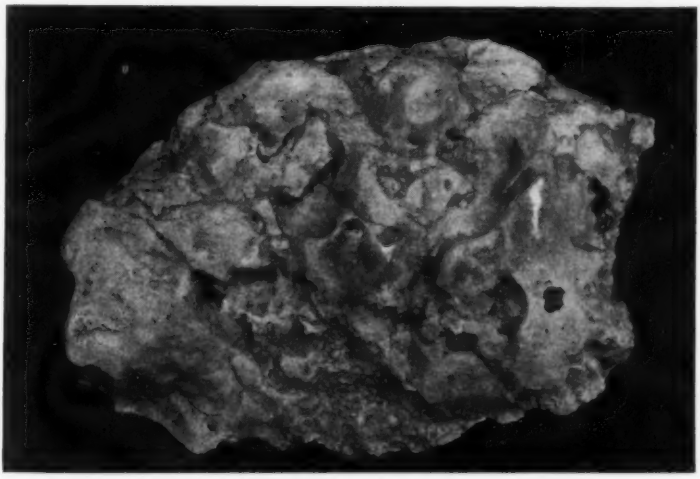

FIG. 6.—Weathered surface of pseudo-conglomerate Tom Sauk limestone, showing the characteristic nodular appearance. ×½.

are probably molds of calcite crystals. In addition to the small amounts of clay, most of the residues contain a few grains of rounded and frosted quartz. Felsite fragments occur in only a few of the residues, but when found they are both large and numerous. The Tom Sauk residues are very similar to those of the Bonneterre in composition but are considerably smaller in amount. The felsitic limestones are unimportant exceptions to the general rule, since local accumulations of detrital felsite are very common in all the sedimentary rocks of the region.

Only one reliable chemical analysis of the Tom Sauk is available, that given by Dake.[9] The specimen, described as "typical dense-textured marble" contained 95.90 per cent calcium carbonate, 4.60 per cent magnesium carbonate, and 0.73 per cent insoluble residue. The amount of magnesium carbonate is probably unusually high.

The fine-grained appearance of the Tom Sauk in hand specimens has already been mentioned. Thin sections of the limestone show that the grain size is, in fact, extremely small. The individual crystals of calcium carbonate range in diameter from 0.002 to 0.008 mm., averaging about 0.004 mm. (see Fig. 7). This is well within the size range of the smallest detrital sediments, the clays, which are defined as less than 0.01 mm.[10] There seems to be some relation between purity and grain size, since the dark-red variety of the limestone is somewhat finer (0.002–0.008 mm.) than the pure white (0.004–0.008 mm.). The fine grain of the Tom Sauk contrasts with the coarser grain of the Bonneterre dolomite, which averages around 1.5–2 mm.

This fine-grained groundmass is not always continuous. In most of the sections there is present a second size group of calcite grains, from 0.02 to 0.06 mm. in diameter. These larger crystals are sometimes scattered or disseminated in the finer grained matrix, but more often they themselves act as a matrix, the aggregate of fine-grained calcite occurring as islands and patches within it. This situation is shown in Figure 8. The Tom Sauk of this thin section is the pure white variety, and the apparent darkness of the islands is due to their smaller grain size. In the darker colored limestones the fine-grained

[9] *Op. cit.*, p. 14.

[10] G. W. Tyrrell, *The Principles of Petrology* (New York, 1929), p. 190.

material is definitely darker in color. The predominant round and oval shapes are well marked and persistent, and the texture is characteristic of the Tom Sauk. The spherules of finer grained material show no structure, radial or concentric. The texture may be due to partial recrystallization of original fine-grained material, or to the presence of remains of foraminifera or other organisms. It is the

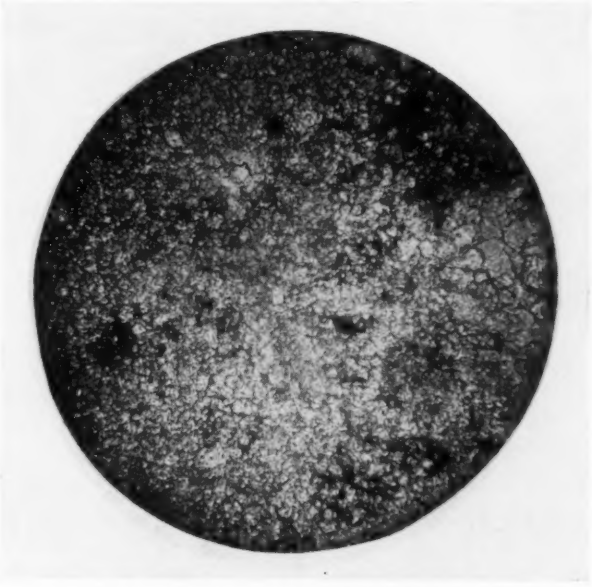

FIG. 7.—Typical fine-grained Tom Sauk limestone. ×190. Ordinary light. The dark spots are red clay.

author's hypothesis, however, that the spherules represent oölites or spherules of calcite in the original sediment.

Veins of still coarser grained calcite present in all the thin sections comprise a third size group of calcite crystals. The grain size ranges from 0.08 to 1.6 mm., averaging about 0.3 mm. These veins and patches are obviously later than the fine-grained material and replace it (Fig. 8).

The limestone appears in the hand specimen completely unfossil-

iferous, but in a few of the thin sections studied there were occasional structures interpreted as fossil remains. These appear as light areas in the dark fine-grained matrix and consist of circles, ellipses, and various irregular curves, including one perfect cross section of a trilobite test.

FIG. 8.—Spheroidal masses of fine-grained calcite in a matrix of coarser grain. Late, coarse-grained, vein calcite replacing both. ×30. Plain light.

ORIGIN

The various peculiarities of the Tom Sauk member already described must indicate an origin somewhat different from that of the rest of the Bonneterre. The earliest opinion was that the limestone was "marble" formed by thermal metamorphism of the dolomites.[11] This theory is utterly untenable. The Tom Sauk is much younger

[11] G. C. Swallow, "Mines and Useful Minerals," *Campbell's Gazetteer of Missouri* (St. Louis, 1874), p. 777; C. R. Keyes, "Report on the Mine La Motte Sheet," *Mo. Geol. Surv.*, Vol. IX, Part 4 (1895), pp. 51 and 105.

than the pre-Cambrian granites and felsites, and post–pre-Cambrian dikes do not occur within the area of Tom Sauk outcrop. Moreover, the limestone lacks the contact silicate minerals which would result from the metamorphism of a dolomite and is rather too fine grained for a metamorphic marble.

Another possible theory is that the Tom Sauk was deposited as a continuous formation over the entire Ozark uplift between Lamotte and Bonneterre time. Subsequent erosion might have removed most of the limestone before the deposition of the Bonneterre. As Dake[12] pointed out, this hypothesis explains the erratic distribution and thickness of the limestone, and its varying stratigraphic position within the Bonneterre. The theory, however, fails to account for the occasional interbedding with Bonneterre dolomite and, even more important, offers no explanation of the nonoccurrence outside the St. Francois Mountains. If the limestone is a distinct formation which once covered the entire Ozark uplift, it is inconceivable that it was completely removed except on the highest part of the old pre-Cambrian surface, in the St. Francois area. Moreover, there is no evidence in deep drillings over the state of such a considerable unconformity as would be involved.

To the writer the most significant fact to be considered is that the Tom Sauk occurs only in the St. Francois Mountains. The key to the limestone formation must be some condition found in the Bonneterre seas only within the igneous knob area. During Bonneterre time the St. Francois Mountains stood higher than the surrounding country, and the igneous knobs were but partly submerged. The pre-Cambrian knob and basin topography, when flooded, produced, apparently, an archipelago with numerous shallow and landlocked bays. This temporary condition, not found to such an extent during the shallower flooding of Lamotte time or in the deeper seas of the post-Bonneterre invasions, is, in the writer's opinion, responsible for the deposition of the Tom Sauk limestone.

Since the Tom Sauk represents an abnormal type of sedimentation during Bonneterre time, it is necessary to consider briefly the deposition of the normal Bonneterre. The formation is made up largely of fine- to medium-grained dolomite, much of it quite pure.

[12] *Op. cit.*, p. 75.

Analyses show that the rock closely approaches the composition of an ideal dolomite. The origin of such widespread dolomites is still a very controversial question. Dolomites of formational extent can only be satisfactorily explained by assuming some theory of origin on the sea floor. From this point of view there are three possibilities: (1) direct chemical precipitation of dolomite or of the mixed carbonates; (2) leaching of calcium carbonate from deposits containing magnesium carbonate, and consequent enrichment in magnesium carbonate; and (3) replacement of calcium in lime deposits by magnesium dissolved in the sea water. The third theory is most widely accepted today and is the one adopted by the writer to account for the formation of the Bonneterre dolomite. Magnesium chloride and sulphate exceed the calcium salts in sea water in the ratio of three to one, and it is easy to conceive of magnesium replacing the calcium, although the exact conditions which control the process are not clear.

There has been surprisingly little investigation of the origin of fine-grained, pure, unfossiliferous limestones like the Tom Sauk. The theories proposed fall into two groups: chemical precipitation by inorganic agencies and chemical precipitation by organisms. The mechanism of direct chemical precipitation has been discussed by Johnston and Williamson.[13] They point out that the surface layers of the oceans, especially in regions of warm climate, are essentially saturated with calcium carbonate. The lime is in solution as the bicarbonate, $CaH_2(CO_3)_2$, formed by reaction between the calcium carbonate and the carbon dioxide dissolved in the sea water. A rise in temperature of the water will cause a loss of carbon dioxide and consequent precipitation of calcium carbonate. Johnston and Williamson mention a number of ways in which such precipitation might take place. Whatever the exact method, a warm shallow sea is an essential requirement for a permanent deposit, for, if the precipitate sinks into colder waters unsaturated with calcium carbonate, it will be redissolved.

Precipitation of calcium carbonate is also likely to occur when

[13] John Johnston and E. D. Williamson, "The Role of Inorganic Agencies in the Deposition of Calcium Carbonate," *Jour. Geol.*, Vol. XXIV (1916), pp. 729–50.

fresh waters highly charged with calcium carbonate enter a shallow sea already saturated with that salt. Lyell[14] reports a crystalline calcareous rock forming in modern times under such conditions, off the mouth of the Rhone.

The subject of organic precipitation of limestone has recently received considerable attention. Vaughan[15] and Drew[16] first suggested that denitrifying bacteria are responsible for the precipitation of the finely divided calcium carbonate which forms extensive mud flats in the shallow waters of the Great Bahamas Bank, and the Florida Keys. These muds consist of fine particles smaller than 0.001 mm., spherulites from 0.004 to 0.006 mm., and oölites from 0.1 to 0.8 mm. The spherulites and oölites are apparently secondary and form within the precipitated fine material. After further study, Field[17] has concluded that the bacteria are of importance only in fresh and brackish water and that the marine muds of the Bahamas are derived from fresh-water lagoons.

From the available evidence, the Tom Sauk limestone might equally well have originated as a chemical precipitate through organic or inorganic agencies. The St. Francois archipelago would have offered excellent conditions for such precipitation and must have been in many respects like the modern Bahamas and Tortugas. In the landlocked bays and basins in which the Tom Sauk was deposited the water was shallow and warmed by the sun. It must also have been brackish or even fresh, if the basin was closed off from the sea, and Field believes that the bacteria are chiefly active in such an environment. Moreover, the waters may have been notably high in calcium; modern river waters normally contain considerable amounts of dissolved lime. The petrology of the Tom Sauk

[14] Sir Charles Lyell, *Principles of Geology* (11th ed., 1872), Vol. I, p. 426.

[15] T. W. Vaughan, "Preliminary Remarks on the Geology of the Bahamas," *Carnegie Institute of Washington, Tortugas Laboratory, Publ. No. 182*, Vol. V (1914), pp. 49–54.

[16] G. H. Drew, "On the Precipitation of Calcium Carbonate in the Sea by Marine Bacteria, and on the Action of Denitrifying Bacteria in Tropical and Temperate Seas," *Carnegie Institute of Washington, Tortugas Laboratory, Publ. No. 182*, Vol. V (1914), pp. 9–45.

[17] R. M. Field, "Microbiology and the Marine Limestones" (abstr.), *Bull. Geol. Soc. Amer.*, Vol. XLIII (1932), p. 142.

strongly suggests a compacted and recrystallized form of a sediment such as Vaughan[18] describes. The fine grain of the limestone and the spheroidal markings seen in the thin sections both suggest the fine lime muds and oölites of the Bahamas. Chemical origin is likewise suggested by the great purity and the small amount of detrital material present.

The difference in composition between the sea water and the fresher water in the closed basins is probably the clue to the non-dolomitization of the Tom Sauk. Numerous analyses cited by Clarke[19] show that modern river waters usually contain several times as much dissolved lime as magnesia, while modern sea water contains a greater amount of magnesia than lime. While the conditions which cause dolomitization are far from well understood, it seems reasonable to assume that, under conditions where sea water high in magnesia causes dolomitization, fresh or brackish water low in magnesia might inhibit it. Consequently, the fine limy sludge deposited in the fresh-water lagoons escaped dolomitization, while the lime deposit in the open Bonneterre sea was completely changed to dolomite. The occasional interbedding of dolomite with the Tom Sauk is easily explained. A period of slightly higher seas or a slight diastrophic disturbance might allow the sea temporary access to one of the enclosed basins.

The evidence that such landlocked bays or basins existed is relatively strong. Pre-Cambrian knobs today completely surround many of the valleys in which the Tom Sauk outcrops, and the streams emerge only through gorges cut in the igneous rock during the latest cycle of stream erosion. Slight diastrophic changes and possibly the formation of bars across the mouths of submerged valleys would have converted many of the pre-Cambrian valleys into landlocked basins, shut off from the sea.

The hypothesis of escape from dolomitization consequent to formation in closed basins explains the major distribution pattern of the Tom Sauk: its occurrence only in the St. Francois Mountains.

[18] *Op. cit.*, p. 52.

[19] F. W. Clarke, "The Data of Geochemistry," *U.S. Geol. Surv. Bull. 770* (5th ed., 1924), pp. 74–109, 125–27.

Varying elevation of the basins and differing lengths of time they were shut off from the sea account for the variable stratigraphic position and varying thickness. The formation in individual basins accounts for the discontinuous occurrence within the St. Francois Mountains. Chemical precipitation, possibly accomplished by bacteria, offers an explanation of the lithologic peculiarities of the limestone.

ACKNOWLEDGMENTS.—The writer wishes to thank Dr. Carl Tolman, of Washington University, for his supervision of the work involved in this investigation and for criticism of the manuscript. The writer is also indebted to Dr. H. A. Buehler and Mr. H. S. McQueen, of the Missouri Geological Survey, for unpublished data on deep drillings and for other courtesies.

GEOLOGICAL NOTES ON THE OCCURRENCE OF "MINNESOTA MAN"

GEORGE F. KAY
University of Iowa

AND

MORRIS M. LEIGHTON
Illinois State Geological Survey

ABSTRACT

This article gives the findings and interpretations resulting from a field review of the "Minnesota Man" site, for which purposes the Minnesota Highway Department removed a portion of the pavement. The authors are convinced that the geological evidence has been properly interpreted by Thiel, Stauffer, Jenks, and Bryan. Two new points are discussed relating to the position of the skeleton lying in accordance with the slight tilt of the beds, and the lack of any vegetable material in the varves that were sampled close to the immediate site of the skeleton.

At the International Symposium on Early Man, held at the Philadelphia Academy of Natural Sciences, March 17–20, 1937, the geological aspects of "Minnesota Man" came up for discussion, particularly in regard to the question as to whether there was evidence that the skeleton had reached the position at which it was found—nearly 10 feet below the surface—by the movement of the enclosing silt beds.

Dr. Ernst Antevs expressed the view previously published by him, that the appearance of the silt, as seen in photographs, strongly suggested "a landslide long after the formation of the silt."[1] On the other hand, Dr. Kirk Bryan, who in 1935 had made a field examination, held the view as published by him, that, "In the vicinity of the site there are no geologic phenomena in sight or processes in action that afford an indication of or reasonable probability of landsliding or similar disturbances which would lead to the intrusive deposition of the skeleton into the silts."[2]

Bryan also held in his publication in regard to the question of the

[1] Ernst Antevs, "The Spread of Aboriginal Man to North America," *Geog. Rev.*, Vol. XXV (1935), p. 305.

[2] Kirk Bryan, "Minnesota Man—a Discussion of the Site," *Science*, Vol. LXXXII, No. 2121 (1935), pp. 170–71.

refilling of a gully, that "there is no evidence that such a gully ever existed in the hill in which the skeleton was found, and the differences between the filling of these gullies and the normal laminated silt are so great that no experienced person could confuse the two."[3]

Because of these opposing opinions and the importance of the questions on which they bear, it was suggested by Dean George F. Kay of the University of Iowa that a field conference be arranged during the summer of 1937. This was favored by Dr. Edgar B. Howard, secretary of the Symposium, and accepted by both Antevs and Bryan and also two other workers in the Pleistocene, Dr. Paul MacClintock of Princeton University and Dr. M. M. Leighton of the Illinois State Geological Survey.

Later it developed that all could not be present at the same time. Antevs, Bryan, and MacClintock visited the site the latter part of June in company with some of the scientists interested from the University of Minnesota, and Kay and Leighton, the latter part of August, in company with Dr. Albert E. Jenks, author of the report on *Pleistocene Man in Minnesota*, and Dr. George A. Thiel, author of the chapter in that report on "The Pleistocene Geology of the Prairie Lake Region." These notes constitute an account by Kay and Leighton of their observations and interpretations.

The examination was made during the afternoon of August 28, 1937, and during the forenoon of August 29. The State Highway Department of Minnesota gave exceptional co-operation by closing the west lane of traffic at the site and by again allowing an excavation to be made in the highway. The reopening of the site was accomplished August 26 and 27 by a University of Minnesota field class in archeology. The site was dug over an area 9 feet wide (east-west) and 11 feet long (north-south), below which the skeleton had been found (Fig. 1). Fortunately, also, the State Highway Department made available the services of Mr. Carl Steffen, the discoverer, to aid in further excavation on August 28 and 29. It will be recalled that while following the grader on June 16, 1931, Steffen had noted the blade of the scraper uncover a white, shimmering shell, and halted the grader to make an examination which resulted in finding the frontal of a human skull lying just beneath the shell fragments.

[3] *Ibid.*

FIG. 1.—View showing the place of the re-excavation made on August 26 and 27, 1937, for the examination of the varved silts lying adjacent to the original position of the skeleton. Cf. with Fig. 3 on p. 10 of Jenks's report entitled *Pleistocene Man in Minnesota*.

Steffen had also been in attendance as representative of the Highway Department on two other occasions—May 7, 1932, and August 2–7, 1932—when post-discovery excavations were made.[4]

Guided by iron stakes, placed on May 8, 1932, opposite the site on either side of the highway cut, and by the tile that lay 22 inches beneath the middle line of the pavement, the excavation, shown in Figure 1, exposed the artificial fill made immediately after the excavation on August 2–7, 1932, and the varved silts immediately adjacent thereto. Thus we were afforded an unanticipated opportunity to see the condition of the strata that had lain closely adjacent to the original position of the skeleton—probably to within about 2 feet. In addition, we examined the sides of the road cut, which had been the only exposures available to observers since August 7, 1932, and we also studied the topography.

Figure 2 is a cross section through the spur in which the road cut is made, drawn along the middle line of the highway with the vertical scale two and one-half times the horizontal. The cross section is based on highway-engineering data which were obtained before the cut was made, and which are given on pages 8, 9, and 11 of the volume by Jenks, already cited. The position of the skeleton in the spur and beneath the road surface, and the slope of the spur above the site are shown.

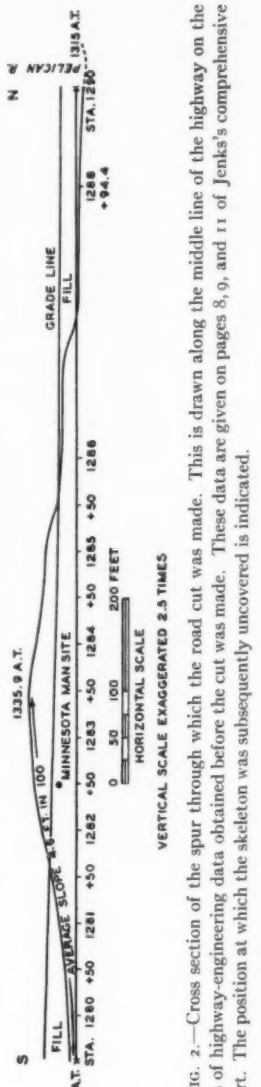

FIG. 2.—Cross section of the spur through which the road cut was made. This is drawn along the middle line of the highway on the basis of highway-engineering data obtained before the cut was made. These data are given on pages 8, 9, and 11 of Jenks's comprehensive report. The position at which the skeleton was subsequently uncovered is indicated.

[4] Albert Ernest Jenks, *Pleistocene Man in Minnesota* (University of Minnesota Press, 1936), p. 15.

p. 10 of Jenks's report entitled *Pleistocene Man in Minnesota*.

Figure 3 is a diagram, drawn to scale, of the east face of our re-excavation. The face was nearly vertical and extended parallel with and close to the present middle line of the pavement, shown by a stripe on its surface. This face did not expose the tile which lies beneath the exact middle of the pavement, but it was found by digging back under the pavement about one foot, as shown in Figure 4. The bottom of the tile lies essentially at the level of the V-shaped groove which was being made by the grader at the time of the discovery.

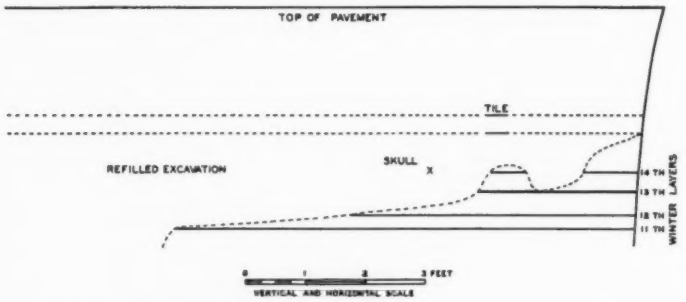

FIG. 3.—Diagram drawn to scale of the east face of the excavation made on August 26 and 27, 1937, showing the close proximity of the varves to the approximate position of the place where the skull was found, as indicated by Steffen and Jenks. The tile was located by digging in 1 foot laterally from this face (see Fig. 4). The skull had been found directly beneath the present level of the tile.

The bottom of the tile lies 28 inches beneath the surface of the pavement, and according to the records,[5] the skull was lying so close to the depression that was made for the tile that it became exposed as Steffen cleared away with his fingers the silt in which he found the shell fragments. The skull was also close enough so that "the weight of the right rear wheel of the grader crushed in the major part of the frontal bone and upper part of the face, but neither the blade nor the wheel touched or exposed any part of the skull or, for that matter, any part of the skeleton."

In Figure 3 is shown the approximate original position of the skull as nearly as could be determined by both Steffen and Jenks,

[5] *Ibid.*, p. 10.

but it should be remembered that the position as indicated here needs to be projected to the vertical plane passing through the tile, one foot away.

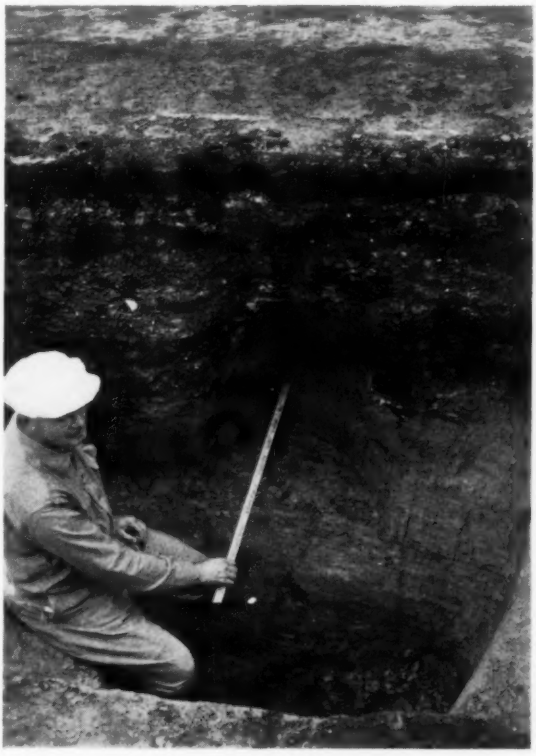

FIG. 4.—View showing the tunnel excavation back under the midline of the pavement for exposing the tile. The skeleton had been found at about the level of the pointer, farther to the left, as shown in Fig. 3.

Figure 3 shows the fill made after previous excavations and the contact of this fill with the varved silts. The contact was drawn to scale.

As shown in Figures 4 and 5, a pit was dug by Steffen, at our request, which penetrated the varved silts at the south end of our

excavation down to the underlying sand, which was found at a depth of $5\frac{3}{4}$ feet beneath the pavement. The measurements agree with the data given on page 16 of Jenks's report.

FIG. 5.—View showing pit dug August 29, 1937. The pit was sunk through the varves beneath the position of the skeleton to the underlying sand at a depth of about $5\frac{3}{4}$ feet below the pavement. This view was taken at right angles to the one shown in Fig. 4.

The varves in the pit were examined carefully from the bottom to the top, which lay about 9 inches below the level of the tile in the south side of the pit. They showed no evidence whatsoever of having been involved in a landslide or any other major movement which would bury the skeleton to a depth of about 10 feet below the sur-

face. The winter layers of clay showed slight irregularities in thickness such as would probably result from "frost-boil" action which prompted the installation of the tile, or from other slight movements.

By count, the uppermost winter layer, which lies at about the approximately determined level of the skull or just above it, is the fourteenth.

The statement published in 1935 by Antevs[6] should probably be quoted in full at this point:

> The silt in which a human skeleton was found at a depth of 9¾ feet, three miles north of Pelican Rapids, Minnesota, is varved silt deposited in front of the melting Wisconsin ice sheet. However, both a sample of the silt and photographs which the writer has seen through the courtesy of Dr. G. A. Thiel, show that the silt bed is disturbed, and this raises the probability that the person was buried by a landslide long after the formation of the silt.

This suggested probability, stated without making an examination of the site, is not concurred in by us after this opportunity of seeing the varves that lie so closely adjacent to the original position of the skeleton, and those exposed in the road cut.

An examination of the engineers' cross sections and profiles—printed in Jenks' report on pages 8, 9, and 11—was also made on the ground, with a view to determining whether or not there had been gullying and refilling, thus accounting for the burial; an examination was also made of the soil profiles exposed in the road cut, on both sides across from the site. The result was that we could see no basis for such an interpretation.

The engineering profiles which were made before the cut was excavated show no gully. There was a very slight depression having a relief of slightly over 1 foot for the entire width of the road cut, which is nearly 100 feet wide. The slope is so low, as shown in Figure 2, and there is so little trace of a previous gully on either side of the cut, that the view that a gully to the depth of the skeleton—about 10 feet—once existed can have the status only of a discarded hypothesis. The varved silts which we exposed in our excavation, close to the position that was occupied by the skeleton, show no evidence whatsoever of the weathering which we might expect if they had been exposed to the air by a gully which was subsequently filled.

[6] *Op. cit.*, p. 305.

The profile of weathering shown on both sides of the highway cut reveals a depth of leaching of about 30 inches, and the other usual elements of weathering and soil-making, all of them normal for late Wisconsin. In this connection we also re-read on the ground the excerpts from Bryan's article printed in Jenks's report on page 184, and found our observations and opinions to be in agreement with his.

The position of the skeleton well back in the spur, as shown in Figure 2, and the very slightly disturbed character of the varves, without marked faulting, folding, or any other evidence of major movement—both in the sides of the cut (see Figs. 19 and 20 of Jenks's report) and next to where the skeleton lay—show the untenability of the landslide hypothesis. We, therefore, find it difficult to explain the depth of the skeleton in any other way than as a natural burial as Jenks and Thiel have interpreted it in their large report.

There are two points in addition to those mentioned in previous publications, which deserve consideration. Ten samples of varved silt taken by Jenks in our presence from within 5 or 6 feet of the original position of the skeleton—from above, below, and at the level of the skeleton—have been examined and reported upon to Jenks by Dr. C. O. Rosendahl, chairman of the department of botany, University of Minnesota. Jenks has kindly provided us with Rosendahl's findings, dated October 22, 1937, which are herewith quoted:

> I have examined the series of samples of silt you submitted from the site of Minnesota Man, and I have also had one of our graduate students who has had several years' experience in fossil pollen studies on bogs go over them. We find no pollen whatsoever, and in all the material examined we have been unable to discover anything that is of unquestioned vegetable nature or origin.

Previously, Dr. Paul B. Sears, professor of botany, University of Oklahoma, had found the endocranial silt to be sterile (see p. 40 of Jenks's report). If the individual had been given a shallow burial in the soil zone comparatively recently, and then there had been movement of material burying her still more deeply, it would seem that pollen might well be found either in the adjacent material or in the silt which later found its way into the skull cavity.

The other point deserving consideration is this. The excavations made on both sides of the road during the field conference in June show that the surface of the sand on which the varved silts lie has a slope to the east of about 8 feet in 91 feet, or 1 in 11. The varves exposed in our August re-excavation under the original position of the skeleton have a similar inclination in the same direction. On page 13 of Jenks's report, he writes: "It was noted that the skeleton appeared to be lowest at the left shoulder, the legs lying slightly higher in the silt." According to Steffen's verbal description made to Kay and Leighton, the skeleton lay with the head to the east and the axis of the body trending slightly south of east. Thus the skeleton appears to have had a position in harmony and in accordance with the slight tilt of the beds, and thus with the bed of the lake in which they were deposited.

SUMMARY

Since no geologist was present at the time the skeleton was discovered, it remains for those familiar with glacial sediments to examine all available geological evidence to see if it is consistent with the reports of the trusted employees of the State Highway Department—who have had much experience in the excavation and observation of materials such as those occurring here—that the layers of silt passed uninterruptedly over the skeleton.

We are convinced from our study that the geological evidence has been properly interpreted by Thiel, Stauffer, and Jenks, and is fully consistent with the testimony of Wright, Steffen, Johnson, and Sellner, as given on page 181 of Jenks's report. This judgment is also in accord with the previously published statements of Dr. Kirk Bryan of Harvard University.

The geological evidence now available, therefore, warrants the judgment that the skeleton reached its position by natural causes. No evidence was seen by us, either in the road cut or in the excavation beneath the site of the skeleton, to support the interpretation that the skeleton was intruded into the silts by landslide or by other earth movements after the silts were deposited. The probability of such intrusion has been suggested by Dr. Ernst Antevs, research associate, Carnegie Institution of Washington, from his examination

of a photograph loaned him by Dr. Thiel, and from his study of samples of silt taken, not in close proximity to the skeleton but in the slopes of the road cut several yards away. Unfortunately, Dr. Antevs did not have the opportunity of examining the varved clays when they were well exposed in the excavations at the very site of the skeleton.

It therefore appears to us from all the geological evidence now at hand that the skeleton may well be as old as the varved silts in which it was imbedded. These silts are interpreted to be of a late Wisconsin stage of the Pleistocene or Glacial period and hence probably eighteen to twenty thousand years old. The skeleton, therefore, appears to rank among the oldest human remains thus far found in America.

ACKNOWLEDGMENTS.—The writers wish to express their deep appreciation of the courtesies extended by Dr. Jenks and Dr. Thiel, of the splendid co-operation of the officials of the State Highway Department of Minnesota, of the invaluable assistance of Mr. Steffen, the discoverer, and of the photographic service rendered by Mr. J. O. Engen, science teacher, Fergus Falls, Minnesota.

WHAT IS IMPLIED BY "DISTURBANCE" AT THE SITE OF MINNESOTA MAN

KIRK BRYAN
Harvard University

AND

PAUL MacCLINTOCK
Princeton University

ABSTRACT

The controversy with regard to Minnesota Man is briefly reviewed: in the present state of knowledge the physical characteristics of the skeleton and the cultural objects are not critical evidence of antiquity, which is a geological problem. The arguments that the skeleton is intrusive into the Late Glacial silts of Lake Pelican are expanded and analyzed. Landsliding as a method of intrusion appears to be improbable and, if it occurred, must have been periglacial and hence of almost the same antiquity as the lake. There is no valid evidence of an ancient filled gully by which intrusion might have occurred.

The authors conclude that there is a prima facie case for contemporaneous deposition of the skeleton and the Late Glacial silts. Other hypotheses involve acceptance of unreasonable contingencies.

INTRODUCTION

Two field conferences were held in the summer of 1937 at the site of Minnesota Man, 3 miles north of Pelican Rapids, Minnesota. As a result of the earlier conference on June 21 and 22, which the writers attended, Ernst Antevs[1] has published his views. At the second conference Dr. G. F. Kay and Dr. M. M. Leighton were present, and they have presented their views in the preceding article.

The finding of the skeleton now known as "Minnesota Man" and the redigging of the site have been completely described by A. E. Jenks[2] in his handsome memoir. Even before its publication a controversy had developed over the possibility of intrusion of the skeleton into the silt beds. The question at issue can briefly be put: Is the skeleton as old as the silt beds? No one questions that the silt beds are the deposit of a proglacial lake, Lake Pelican, which lay between the Altamont-Gary system of moraines and the Big Stone moraine. That the lake existed when glacial ice lingered in the vicin-

[1] "The Age of the 'Minnesota Man,'" *Carnegie Inst. Wash. Yearbook*, No. 36 (1937), pp. 335–38.

[2] *Pleistocene Man in Minnesota* (University of Minnesota Press, 1936).

ity is probable from the varved character of the silt layers. According to G. A. Thiel's[3] review of the evidence, an ice lobe lay in the Red River Valley to the west and was actively building the Big Stone moraine during the lake period. There were doubtless many complications and minor incidents on which further light will be shed by the work of Ernest Berg, which is still in progress. Based on the broad features outlined above, the silt thus has an antiquity greater than that of Lake Agassiz, a much larger lake that formed as the ice lobe within the Big Stone moraine retreated. The beginning of Lake Agassiz is set by Leverett and Antevs[4] at eighteen thousand years ago, so that the silt beds have a somewhat earlier date. Such an antiquity for man in America is inconceivable to many students of the problem, and there is a search for some other conclusion. On cultural grounds H. J. Spinden[5] has made a general attack on the interpretation of all finds implying antiquity greater than about three thousand years. Ales Hrdlička[6] has attacked the Minnesota case with an argument that is geologic and also anatomical, to which Professor Jenks is making a reply in the same *Journal*.

Antevs has advocated intrusion into the silt beds first[7] by landsliding and second[8] by either landsliding or gullying, whichever is the better. The present authors believe that any open-minded scientist, on reading Jenks's memoir, must agree that the skeleton is that of no common fifteen-year-old girl, and that her extraordinarily large teeth are hardly compatible with her alleged status as an ordinary Sioux maiden. However, Late Glacial man in Europe is quite modern in his physical aspect, and there is no logical reason for expecting that man of the same age in North America should not have physical characters well within *Homo sapiens*. The cultural objects found with her consist of a bone knife and two shells apparently worn

[3] "Pleistocene Geology of the Prairie Lake Region," in Jenks, *op. cit.*, pp. 17–33.

[4] See opinions quoted by Thiel, *ibid.*, pp. 32–33.

[5] "First Peopling of America as a Chronological Problem," *Early Man*, ed. G. G. MacCurdy (Philadelphia: J. B. Lippincott Co., 1937), pp. 104–14.

[6] "The Minnesota Man," *Amer. Jour. Phys. Anthrop.*, Vol. XXII (1937), pp. 175–99.

[7] "The Spread of Aboriginal Man to North America," *Geog. Rev.*, Vol. XXV (1935) pp. 300–309.

[8] "The Age of the 'Minnesota Man,'" *loc. cit.*

as ornaments. Such objects in themselves are not distinctive of any one culture and might pertain to an individual of almost any primitive hunting tribe. They afford little basis for argument as to the relative antiquity of the people to whom she belonged. One of the shells is that of *Busycon perversa*, a Gulf Coast marine species, and its presence indicates that her people were in contact by trade or otherwise with warm regions to the south. Our knowledge of no ancient culture in North America is so complete that we can assert that such relations were impossible in Late Glacial times; nor, on the other hand, that these implied relations with the South are so characteristic of some later culture as to imply that the possession of the shell indicates that the individual belongs to a late culture.

The fragments of animal bones which Professor Jenks so painstakingly recovered from his pits are those of a wolf, a loon, a turtle, and perhaps a muskrat. Together with the cultural objects, the bone knife—which is part of an elk antler—and the shells, the fauna would indicate, as Antevs[9] points out, a cool but not an arctic environment. However, if all these bone fragments came from a medicine bag, as Jenks suggested in his report, they may have been brought into the region with the warm-climate marine shell, *B. perversa*. Even if the elk, loon, and wolf are of local origin and represent the fauna of the region, they may have been summer migrants. We have no reason to believe that in the Late Glacial period the summers were any colder than our winter, and all these animals, except *Busycon*, but including the turtle and the muskrat, survive the winters of northern United States and southern Canada. Late Glacial summers may have been shorter than our summers but as warm.

"DISTURBANCE" OR INTERNAL DEFORMATION

With this review before us it appears that the critical evidence as to the antiquity of Minnesota Man rests on the geological occurrence of the skeleton. As the bones lay too deep to have been buried in a grave excavated from anywhere near the present surface, the geologic evidence as to whether or not the enclosing deposit was "disturbed" becomes crucial. Now disturbance is used in several senses. In archeological parlance the term implies that the area or the beds

[9] *Ibid.*

have been disturbed by the intervention of man, and usually that man has dug a hole for a grave or other purpose and that the hole has been refilled by man or by natural causes. It is obvious that Antevs is not using the term in this sense. He believes that there may or may not have been a grave; i.e., a "disturbance" in the usual archeological sense. His position is that the beds are disturbed—or, more precisely, "internally deformed"—by natural processes of slipping or sliding; that the girl, dead or alive, was thus entombed; and that the entombment may have occurred in comparatively recent time.

The authors propose to explore the possibilities of these hypotheses. The varved sediments occur as a 15–25-foot blanket covering a glacially constructed topography of low, irregular hills and rolling uplands, separated by constructional depressions now containing swamps and ponds. In other words, the area has a largely insequent drainage. Thiel[10] implies that the varved beds were deposited on an uneven lake bottom and in this way came to have the various topographic positions and undulatory deformation seen in the field. This may well have been the case, but another equally plausible suggestion comes to mind. Prairie Lake now occupies one of the pits of the pitted outwash plain of this district. This means that during deglaciation ice blocks were left strewn about the area and more or less covered with drift. If the proglacial Pelican Lake came into existence at this time, and if the ice blocks were buried or were loaded enough to keep them from floating up, the lake sediments may have been deposited on a flattish surface. After the lake was drained and the ice blocks melted, the drift and lake beds would settle slowly into depressions thus made. During the settling, slight distortion of the material, including the lacustrine sediments, would probably take place. During the conference on June 22, Mr. Ernest Berg showed us a locality some 4 miles south of the site where the silt beds are overlain by glacial till. Here deformation by override of ice is unquestionable. Mr. Berg's work will doubtless bring out many other facts that will illuminate the problem of the gentle deformation to which the beds have been subjected.

Antevs' main point, brought out by his excavations in the cut which were witnessed by us, is that the clay layers are smeared and

[10] In Jenks, *op. cit.*, Fig. 21 and p. 23.

in places show slickensides, and that some of the sandy layers show lumps of sand and crenulations of the laminae. All these things demonstrate internal movements in the beds. We cannot withhold our admiration of Antevs' technique in discovering and demonstrating these small structures, and we have no doubt that such features invalidate the locality as a place for measuring varves for geochronological purposes, as Antevs stated in the field. The question which arises in our minds has to do with the interpretation of these evidences of internal movement. Do they necessarily imply a "disturbance" of the beds sufficiently great and so timed as to lead to the intrusion of the skeleton into the beds to a depth of 10 feet? Obviously Antevs is not completely convinced, else he would not also put forth the hypothesis of burial in an ancient gully.

Considering that the silt beds are undulatory to as much as 50 feet in a quarter of a mile, and across the cut at the site to about 11 feet in 100, internal movements must have occurred. Part of the "internal deformation" must be due to the gliding of one bed over another in the distortions of beds and between beds required by the present undulatory position.

Further, we must consider the conditions of deposition of varved silts. To produce even and regular annual layers (varves) a lake must be deep enough so that the material laid down in the winter season is not disturbed by wave action during the succeeding summer. Now Lake Pelican was apparently relatively small and shallow. The sand bed at the base of the section at the site is fairly coarse and in places contains small pebbles. It must have been considerably reworked if not wholly deposited by wave action, implying that the lake was shallow. The succeeding varved silts are relatively coarse and the layers consist of fine sand or silt (summer component) and clay (winter component) which together are on an average about 4 inches thick. We must believe that wave action during the summer was important in order to spread the fine sand and silt of the summer component over the lake bottom. The most regular varves are found in the lower 4–5 feet of the section, just above the sand and forming the horizon at which the skeleton was found. Here Antevs counted twelve annual layers in our presence, and here in our opinion the evidence of "internal deformation" is the least evident. Above this

zone the varves are thicker and there are crenulations of the laminae, lumps in the sand, and the winter layers are less well marked. The increase in the thickness of the annual layers and their increased grain size testify to changes in the lake toward shallowness and increased wave action. Much of this "disturbance" appears to us to be due to the breakup of the winter components by wave action in the following summer season.

Thus the minor irregularities in the varves which Antevs has demonstrated appear to us to be due to the following causes: (1) internal movement in the beds associated with their undulations—the undulations in turn caused by differential settlement on an uneven bottom and perhaps also in places to override by ice as shown by Berg; (2) irregularities in deposition presumably due to wave action in a shallow lake.

HAS LANDSLIDING TAKEN PLACE?

We see in the topography no evidence of landsliding or large-scale horizontal or vertical movements. The silt laminae, with the minor complications in their regularity that Antevs has found, extend to the slopes of the hills and disappear in the soil zone on the slopes. Landsliding has left no trace in the present topography, and, if it ever took place, the topographic irregularities have been erased by the development of the present hill slopes. The landsliding postulated by Antevs must be older than the present topography and thus of quite respectable antiquity.

The Late Glacial silts and clays, especially if varved, are particularly liable to landsliding in positions where they can become saturated with water or are sharply undercut by the lateral planation of streams or by wave action. However, these beds are thin, from 15 to 25 feet thick, and rest on a coarse sand. The underlying sand affords ready drainage, so that it is not easy to attain that state of saturation which would induce sliding. The existing ponds and lakes are too small and shallow to form by wave action strong and numerous bounding cliffs.

If there has been extensive landsliding, it must have occurred during a climatic regime different from that of the present. It is easy to conceive that if the underlying sand bed were frozen and the

silt beds alternately frozen and thawed, extensive landsliding might occur. Such conditions would obtain in the fall and spring of the semiarctic or periglacial climate that must have existed during Late Glacial time. Thus in the period immediately following drainage of Lake Pelican, when the silt beds were less compacted than now and when the slopes adjacent to recently melted ice blocks were still steep, local landsliding induced by extreme frost action might have occurred. However, if landsliding occurred at this period it dates back to the time of the Big Stone moraine or some eighteen thousand years ago. A skeleton entombed by this postulated period of landsliding is so nearly of the same antiquity as one entombed during the life of the lake that from our present viewpoint on the age of man in America there is little or no difference.

HOW WOULD LANDSLIDING INDUCE INTRUSION OF SKELETON?

Although the writers reject landsliding as the process of burial, it is worth while to consider by just what mechanism landsliding could have functioned so as to cause intrusion of the skeleton into the silt beds to a depth of 10 feet. It is obvious that the landslide may have operated by at least two methods. A crack may have opened above the site, and after intrusion it may have been closed by further movement. Or a sliding mass 10 feet or more thick may have moved laterally over the site. Not only are there these two methods of intrusion, but also the girl may have been either living or already dead at the time. Thus we have four possible contingencies to explore.

First, however, it is important to have in mind the position of the body. As described by Jenks,[11] the skeleton lay on its left side with the face turned somewhat upward so that the right part of the frontal bone was uppermost. The legs lay together, the knees slightly flexed and the upper legs just noticeably flexed forward at the pelvis. The right arm was bent at the elbow so that the right forearm lay to the left of the vertebral column and the upper arm lay parallel to it. The left arm was beneath the ribs and practically straight beneath or just in front of the body. The left shoulder was the lowest part of the skeleton and the legs lay slightly higher.

[11] *Ibid.*, p. 13.

If a vertical crack opened, we must conceive that the body fell into the crack together with the three cultural objects. If the girl were alive she must have been so surprised or so stunned by the fall that she kept both her legs and her arms close to her body so that they were not later torn away but were found in a relaxed position close to the trunk. Also the two shells and her bone knife fell with her and were not separated from her. If she were dead she must have been dead but a short time, else, whether buried by her people or lying unburied on the surface, her bones would have become disarticulated and scattered by the fall and the two shells and her bone knife would probably have been lost. The possibility of the breakup of the skeleton is the more probable in that her bony structure was not yet complete and the epiphyses of her long bones were attached only by quickly decaying cartilages. Yet Jenks's[12] data show that all the principal parts of the body were present except the feet and one hand. As the bones of the extremities are small, they are easily lost and may not have been recovered. Also in young individuals they are easily decayed after burial, and the absence of these parts does not invalidate the conclusion that the body is intact. It is so complete and was so laid out on its side and parallel to the bedding planes as to force us to believe that the body landed at the bottom of an open crack in a relaxed position. All the possible positions in which the body might have lodged in a crack or the numerous positions which a live person struggling to climb out might have assumed are barred. We are forced to believe that the crack closed when the body was relaxed and lying parallel to the bedding planes. This is a set of requirements so special as to make incredible the hypothesis that the girl, dead or alive, fell into a crack 10 feet or more deep.

We must consider also the state of the skeleton if, after falling into such a crack, it were entombed by the closing of the crack by further sliding. A crack wide enough to admit the body must have been closed without inducing pressure at the bottom sufficient to crush the bones or to scatter the skeleton or to disrupt the body along the planes of movement.

If we explore the possibility of intruding the skeleton by purely lateral movement, we must assume that the girl, alive or dead, was

[12] *Ibid.*, Figs. 27 and 28.

in a position below a hill and that the hill or part of it moved toward and over her, or over her grave. In the gentle topography of the present such a situation is impossible. We must assume some set of conditions belonging in the past. If we assume that Lake Pelican had recently been deserted by water and that ice blocks had recently melted, the slopes of the ice-block holes may have been steep enough to induce sliding. But the draining of Lake Pelican was in a period so remote and so close to the time of its existence that entombment at such a time yields us a date for all practical purposes as remote as if the girl were contemporaneous with the lake.

That the present undrained depressions of the area once contained lakes and that the existing lakes once had higher levels than they do today is obvious from the numerous abandoned shorelines. As suggested by Bryan during the conference, the waves of these lakes at their higher levels eroded their shores and produced cliffs. To a lesser extent they are doing this at present. A cliff in unconsolidated material and particularly in varved silts is an oversteepened slope where landslides are common features. If the landslide started from a lake cliff we must suppose that the girl was walking on the lake shore and fell, or was sleeping on the shore at the instant of the slide. Or if she were dead she must have been buried at the foot of the cliff. Whatever the reason for the position of the body, a mass of earth more than 10 feet thick passed over the body without separating from it the three cultural objects or without distributing or crushing the bones. It may be argued that if a body were buried from 1 to 3 feet deep, the landslide could pass over it without disturbing it. Under this hypothesis the body must have been buried in the wave-cut glacial silts and not in beach sand or in any debris eroded by subaerial processes from the cliff, as neither of these types of material was found. However, why should a plane of movement be selected just above the body but not so high as to include beach sand or any debris eroded from the cliff? Obviously, of all the possible planes of movement only one was used, and that one just above the body in varved silt and below any material from the beach. If some of the beach material were present, or if the bones had been smeared out over an area 10 feet or more in length in the direction of the slide, this hypothesis would have more weight.

We should also consider what lake level would be most likely to produce the cliff from which the proposed slide is to originate. On the shores of near-by lakes, and particularly Prairie Lake, abandoned beaches are common at levels of about 5, 10–15, and 25–30 feet above the ordinary levels of the present day. The 5-foot beach may be the result of unusually heavy storms, or it may be due to higher levels in the immediate past. The other beaches seem to record definite ancient periods of high-water levels. As many of the lakes are without outlet or have insignificant outlets, these higher levels record periods of high ground-water level, which condition implies climatic conditions wetter than the present.

If we consider these higher levels of the lakes with respect to the site, further difficulties with the landslide hypothesis arise. Prairie Lake lies west of the site and only a few hundred feet distant. The altitude of ordinary low water in Pelican River at the highway bridge is 1,312.2 feet and of Prairie Lake 1,313 feet; the top of the little hill is something over 1,340 feet, with a maximum on the highway of 1,335.9 feet, and the skeleton lay 9.5 feet lower, or at an altitude of 1,324 feet. It is obvious in the field that at the level of the 5-foot beach Prairie Lake formed no cliff. At the level of the 10–15-foot beach it may have formed a cliff, but the base of this cliff was at an altitude of 1,325 feet, or just at the level of the skeleton. At the level of the 25–30-foot beach the base of the cliff would have an altitude of not less than 1,338 feet, or 16 feet above the skeleton. Thus at the stage of the 10–15-foot beach we must believe that extensive sliding occurred on a zero gradient over a distance of 500 feet, whereas at the 30-foot stage the little hill would be partly surrounded by water and the position of the skeleton below water level.

In the foregoing the evidence for landsliding as a method of entombment of the skeleton has been reviewed. Unless the sliding is to be put back into the time immediately after drainage of Lake Pelican and attributed to the effect of periglacial action, there is no body of fact which brings the hypothesis into the realm of reasonable belief. If the landsliding dates back to the periglacial climate, the antiquity of the skeleton is virtually as great as under the hypothesis that the girl fell into Lake Pelican during its period of existence.

INTRUSION OF THE SKELETON BY GULLYING

It seems obvious that Antevs realizes the weakness of the hypothesis of landsliding, for he revives the hypothesis of burial in a filled gully. As pointed out by Bryan,[13] the development of the present gentle and soil-covered slopes on the silt beds was largely accomplished by weathering and rain wash. However, in this process gullies have been opened and later filled. One of them in the roadcut ½-mile south of the site is 5 feet deep and 20–30 feet across the top. Shallower gullies occur elsewhere. The filling of these gullies is of re-worked unlaminated silt with small nodules and veins of lime carbonate. The color is distinctive and browner and more yellowish than the normal varved silt. There is no evidence that any of these filled gullies reached a depth of 9 feet, yet Antevs says:

> Since the skeleton occurred at a depth of 10 feet, the girl may not have been buried by her people from the present ground surface. She can have been buried, however, at a time when the surface was lower; and the thick overburden can be the result of downwash of silt and soil over the grave by rains or of sliding over the grave, as I originally held.[14]

Antevs, by postulating a burial in the bottom of a gully, creates a new variation to the hypothesis. Such a site for a grave seems unusual and certainly not in accord with ordinary Indian, and particularly Sioux, customs. The grave could hardly have been deeper than 3 feet—an extreme for primitive burials—and was more likely 1 foot deep. The gully must thus have been 7–9 feet deep. If it corresponded to the known filled gullies of the area, it was 20–30 feet or more wide. As no filled gully of such dimensions crops out on the banks on either side of the road, this postulated gully must have had a trend parallel to the road. By reference to Figures 2 and 22 of Jenks's memoir and the United States Geological Survey's Pelican Rapids topographic sheet, it is obvious that a gully parallel to the road must have had a slightly southwesterly course. It could have originated only at the top of the crest on the road at elevation 1,336 feet and have flowed southwesterly to the depression south of the site at an elevation of 1,318 feet. It would have had a fall of 18 feet in a dis-

[13] Kirk Bryan, "Minnesota Man—a Discussion of the Site," *Science*, N.S., Vol. LXXXII (1935), pp. 170–71.

[14] "The Age of the 'Minnesota Man,'" *op. cit.*, p. 337.

tance of about 450 feet. On this gradient the upper part of the gully is to be 7–9 feet deep at the site, or at a distance of 100 feet from the crest of the hill. Not only is this set of circumstances improbable but the known gullies of the region are filled with a distinctive material easy to detect and obviously different in texture from the normal varved silt.

It is true that the material of the cut is now removed, but Jenks states:

> Wright [the foreman] told me that when he came to the spot where the skull had been exposed by Steffen, he at once noticed and spoke of the smooth layers of silt lying from the middle of the road, where the grader had cut deepest, to the shoulders of the road, where the cutting began.[15]

Also quoting Wright:

> We noticed that it did not look as if it had been buried as the ground had never been broken above and around it. . . . . At the time Mr. Steffen finished digging and removing the bones he stated that it had never been buried because the layers of earth had not been disturbed. . . . . At the time I paid special attention to the layers of earth above and through the entire cut, they were never disturbed before we dug them. The layers ran through the cut and were exposed by the grader. . . . .

The authors have talked to Carl Steffen, a very intelligent man, who assured us with much circumstantial detail that the layers of the varved silt were exposed without break in the shallow cut being made by the grader at the time. If a gully had existed more or less parallel to the road, its yellowish, lime-stained filling would have been distinctive and would have broken the even bedding which the members of the road crew describe.

It is beyond our belief that Carl Steffen and other members of the road crew, who know these banded silts from years of experience, could have cut through such a gully without being aware of it. It is beyond our belief that Professor Jenks and Professor Thiel in the two subsequent excavations could have failed to find and locate such a gully if it ever existed. As Kay and Leighton[16] point out, there is no existing evidence for such a gully and the excavation made by them showed varved silt undisturbed (except for the minor deforma-

[15] *Op. cit.*, pp. 13–14.

[16] G. F. Kay and M. M. Leighton, "Geological Notes on the Occurrence of 'Minnesota Man,'" *Jour. Geol.*, Vol. XLVI (1938), pp. 268–78.

tions noted by Antevs) to a point not over 2 feet distant from the position of the skull. Too many observers familiar with the banded silt from which the re-worked silt of filled gullies is easily discriminated have made detailed observations for anyone to take seriously the hypothesis of burial of the skeleton or of covering of a grave by the filling of a gully.

SUMMATION OF ARGUMENT

The hypotheses brought forward to explain the deep burial of the skeleton of Minnesota Man by intrusion into the varved silts of Lake Pelican all require a belief in combinations of circumstances beyond reasonable probability. In regard to "disturbance," the writers agree that there has been "internal deformation," or "slipping," if that term is preferred, within the varved silts, but believe that it was of trivial extent and of Late Glacial age. They therefore return to Bryan's position:

> In the vicinity of the site there are no geologic phenomena in sight or processes in action that afford an indication of or reasonable probability of landsliding or similar disturbances which would lead to the intrusive deposition of the skeleton into the silts.[17]

In regard to the possibility of burial in a gully, the writers reject such a possibility on the ground that the existence of a gully at the site has not been proved and that too many observers in whom we have confidence testify to the contrary.

The hypothesis that the girl, whose bones are the sole known evidence of her race, fell into the lake, was drowned, and was buried by the processes of rapid deposition then in action is not only plausible but requires belief in no unusual concatenation of circumstances. Furthermore, Kay and Leighton[18] point out that the position of the skeleton with its legs higher than the head agrees with the local dip of the silt beds. It lay parallel to the bedding and was apparently tilted with the beds in their deformation—a further testimony to contemporaneity of the skeleton with deposition of the silt.

Many students of the problems of ancient man find difficulty in accepting the conclusion that a race of men lived in Minnesota in Late Glacial times. Nor do we feel that such an important conclusion

[17] *Op. cit.*, p. 171. [18] *Op. cit.*

can be completely established on one find. We look forward to additional finds in beds of similar age. Our position is that a skeleton of distinctive physical type has been found in Late Glacial silts, and there is a prima facie case that it is contemporary.

It is always possible to cast doubt on the provenance and geologic horizon of a fossil by an appeal to remote contingencies. Only where fossils are abundant can a complete answer be made to such arguments by inviting all doubters to collect for themselves. Abundance has made the marine invertebrates the standard horizon-markers of geology. Vertebrates—and particularly the primates, including man—are rare fossils. Each find is due to a fortunate combination of circumstances in the deposition, preservation, and subsequent exposure of the bones. Thus remote, but not unreasonable, contingencies lead to the occurrence and finding of the fossils, and equally remote, but not unreasonable, contingencies may blur the evidence of the geologic horizon. However, the circumstances of the finding of Minnesota Man have been so carefully documented and investigated through the zeal of Professor Jenks that there seems to be no geological basis for any reasonable doubt as to the contemporaneity of the skeleton and the silt.

If in the future the race and culture represented by the skeleton should, on evidence derived from other finds, be proved to be of a date later than the silt of Lake Pelican, then, and then only, would we be justified in accepting some one of the explanations, reviewed above, which on the strictly local evidence appear to involve improbable and unreasonable contingencies.

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WAS "MINNESOTA GIRL" BURIED IN A GULLY?

ERNST ANTEVS
Carnegie Institution of Washington

ABSTRACT

Not only is there no direct evidence of a Late Glacial age of the "Minnesota Girl" but drowning in a glacial lake is a far less reasonable assumption than a postglacial or modern burial in a gully.

The "Minnesota Girl" from Pelican Rapids is believed by her discoverers and biographers to have drowned in a glacial lake near the border of the last retreating ice sheet and to have become embedded in the varved silt.[1] Her importance lies in the fact that, if these claims are correct, she would be the first-known American and, roughly, twenty thousand years old, or older than any American artifacts of verified dating. The occurrence with the skeleton of a pendant made from the shell of the marine conch *Busycon perversa* proves trade relation with the 1,100-mile distant Gulf Coast. These conditions have important implications and raise the nice question of the time of immigration of man. Could man have spread from Asia, through Alaska and Canada, after the last climax of the Keewatin ice sheet in the Des Moines–Dakota ice lobes, roughly, twenty-five thousand years ago, and have established trade connections between the Gulf of Mexico and west-central Minnesota by about twenty thousand years ago? Or is not twenty thousand years ago about the time that a route can be expected to have been opened between the shrinking Cordilleran and Keewatin ice sheets, implying that man must have arrived prior to the last Keewatin ice expansion and perhaps prior to the first Keewatin culmination (= Iowan glaciation)?[2a, 3] Faced by these consequences and problems, should we re-

[1] A. E. Jenks, *Pleistocene Man in Minnesota: A Fossil Homo sapiens* (University of Minnesota Press, 1936).

[2] W. A. Johnston, "Quaternary Geology of North America in Relation to the Migration of Man," *The American Aborigines*, ed. Diamond Jennes (University of Toronto Press, 1933), pp. 9–45; see esp. pp. 22, 42, 44.

[3] Ernst Antevs, "Climaxes of the Last Glaciation in North America," *Amer. Jour. Sci.*, Vol. XXVIII (1934), pp. 304–11.

quire positive, irrefutable proof that the girl reposed beneath entirely undisturbed varves of glacial silt, or should we disregard the fact that we do not know the nature, age, and condition of the superimposed beds and be satisfied with a mere possibility that she was drowned in the ice lake—in itself a very improbable event because of the barren glacial environment?

The "Minnesota Girl" was found in June, 1931, by a state highway crew while they were making a V-shaped trench in a road surface in order to remove a "frost boil" in a cut 3 miles north of Pelican Rapids. The road cut itself had been made in 1929 by other men, who have supplied no information about the excavated material. The V-shaped trench, which was $2\frac{1}{2}$ feet deep in the center of the road, was made with a grader hauled by a tractor. A shining clamshell, uncovered at the bottom of the trench, led to the discovery of the skeleton just beneath, or at a depth of 10 feet below the original ground surface. The skeleton was removed by the men, who testify that the overlying material (of which they could have seen at most 2 ft.) was undisturbed varved glacial silt.[4] However, it is doubtful if at this stage anybody could have determined whether or not the overlying beds were originally undisturbed, for they were by now almost entirely removed, and what remained had been heaved by frost, pressed by the weight of traffic and the tractor, and smeared and crumpled by the grader blade. At any rate, the slim and only opportunity to study the overlying beds and the mode of occurrence of the skeleton went by; and as a consequence there is no valid observation to the effect that the girl was embedded in varved silt during its deposition in the Late Glacial ice lake. Therefore, for those who, like the writer, require direct evidence, the main point of dispute concerning the "Minnesota Girl" is settled. In contrast to the previous positive statements by Jenks,[5] Thiel,[6] and Bryan,[7]

[4] Jenks, *op. cit.*, pp. 7, 10, 13, 14, 181.

[5] *Ibid.*, pp. 2, 177.

[6] G. A. Thiel, "The Pleistocene Geology of the Prairie Lake Region," in *ibid.*, pp. 17–33; see esp. p. 33.

[7] Kirk Bryan, "Minnesota Man—a Discussion of the Site," *Science*, Vol. LXXXII (1935), pp. 170–71; "Ancient Man in North America," *Geog. Rev.*, Vol. XXVII (July, 1937), pp. 507–9.

Bryan and MacClintock[8] now aim to prove the girl's Late Glacial age by indirect evidence.

As pointed out by the writer,[9] the surveyor's cross-section profiles show a shallow gully directly over the site,[10] the roadway being located so that its center parallels and coincides with the deepest part of the gully. This gulch, which started near the crest of the ridge, or less than 100 feet to the north, was entirely removed when the 95-foot wide road cut was made. On slopes of such easily eroded material as the glacial silt composing the ridge, gullies form quickly during rains if the sod is broken or affords insufficient protection; and they become filled by wash, slump, and slide. It is entirely possible that a gully some 10 feet deep has existed on the site. The body of the girl can have been buried by her people in the gully in varved glacial silt, or, if the erosion had reached the level of the site, in postglacial wash. Or the girl can have died in the gulch and become covered by wash and slump.

The fauna represented by ornaments, tools, and "medicine," indicates modern climatic conditions; and *Busycon perversa* from the Gulf of Mexico, which frequently occurs in Illinois and Ohio in Indian mounds from A.D. 1000 to 1500,[11] suggests that the "Minnesota Girl" belongs to that age.

[8] Kirk Bryan and Paul MacClintock, "What Is Implied by 'Disturbance' at the Site of Minnesota Man?" *Jour. Geol.*, Vol. XLVI (1938), pp. 279–92.

[9] Antevs, "The Age of the 'Minnesota Man,'" *Carnegie Inst. Wash. Year Book 36* (1937), pp. 335–38.

[10] Jenks, *op. cit.*, Fig. 4, p. 11.

[11] Antevs, "The Age of the 'Minnesota Man,'" *loc. cit.*

AN ANCIENT LANDSLIP AT SAIDMARREH IN SOUTHWESTERN IRAN

J. V. HARRISON AND N. L. FALCON

ABSTRACT

A large landslip[1] occurred in prehistoric times in the Saidmarreh district of Luristan (lat. 33° 0′ N.; long. 47° 39′ E.). About 5 cubic miles of Lower Miocene limestone and Eocene marly limestone fell off the northern flank of the Kabir Kuh anticline and left a scar about 9 miles long. The sheet of debris, 64 square miles in area, blocks the synclinal valley and has ridden up and over the plunging end of the anticlinal range known as Kuh Dufarash. Three lakes were impounded but have since been drained, either by seepage or as their overflow cut a gorge through the obstruction. The large angular blocks occurring as far as 9 miles from their point of origin, the big area occupied by the landslip material, and the considerable vertical as well as lateral carriage it has experienced make this landslip of more than local interest.

INTRODUCTION

Luristan is a province in southwestern Iran (Persia) bordering Iraq. It is mountainous country with ranges up to 9,000 feet high whose form is closely controlled by simple, almost symmetrical folds in which the limestone bodies, being strong and resistant, are the feature-making rocks. The sequence of strata is as follows:

Fars series (younger than Lower Miocene)	Red marls, sandstones, and conglomerates above, with red and gray marls, thin limestones, and gypsum below
Asmari Limestone (Lower Miocene–Oligocene)	Well-bedded and massive limestone about 1,100 feet thick
Eocene–Upper Cretaceous	Thin-bedded limestones with calcareous shales, marlstone, and rubbly limestone about 3,000 feet thick
Middle Cretaceous limestone	Well-bedded and massive limestone more than 2,000 feet thick

The principal chain is called Kabir Kuh and is an anticlinal feature sculptured in Middle Cretaceous limestone forming a large whaleback mountain (Fig. 1, block diagram). On its flank lies a zone

[1] J. V. Harrison and N. L. Falcon, "The Saidmarreh Landslip, Southwest Iran," *Geog. Jour.*, Vol. LXXXIX (1937), pp. 42–47.

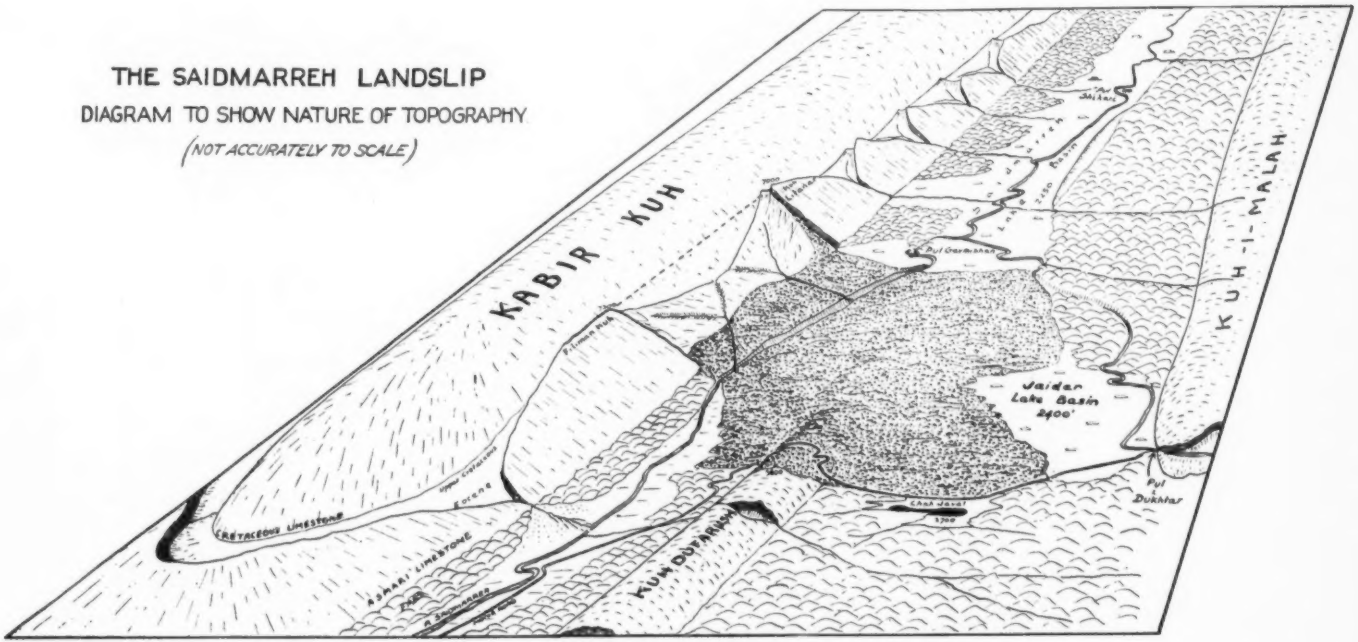

FIG. 1.—Block diagram of the landslip

of cols in which the Eocene–Upper Cretaceous marly body has been more rapidly weathered away. Then comes an imposing sierra formed by the Asmari limestone which has weathered out. The valley on the northeast is controlled by this formation upon which a relatively thin skin of Fars remains after the course of differential erosion. Fragments of river-cut benches are preserved at two levels. At the eastern end the syncline is about 5 miles wide, and the Asmari limestone anticlinal range of Kuh Dufarash forms the northeastern wall, but, owing to the northwestward plunge of this structure, the syncline widens out to nearly 10 miles in a westerly direction where the Asmari limestone hogback of Kuh-i-Malah forms the northeastern slope of the syncline. Running along the syncline from the northwest is the Saidmarreh River, while cutting across the Kuh-i-Malah anticline from the northeast comes the river Kashgan. Both are perennial and carry down large floods in the spring.

THE LANDSLIP DEBRIS

Upon these simple geologic foundations is superimposed a series of uncommon surface deposits. The most conspicuous is a broad apron spread out from south to north completely covering the valley between the plunging end of Kuh Dufarash and Gwardalanga with a wild confusion of disorderly limestone blocks. This apron of debris has an area of 64 square miles. Its width from west-northwest to east-southeast reaches a maximum of $12\frac{1}{2}$ miles, and at right angles one lobe is 9 miles across. The periphery of the sheet amounts to 43 miles. In the gorge cut through it by the river 400 feet of detritus rests upon the underlying Fars, and in a ridge near by it rises another 600 feet, suggesting a maximum thickness of 1,000 feet. Large blocks of limestone mingle with fragments of smaller sizes down to that of dust. All the pieces are angular (Fig. 2). The surface of the sheet falls from 4,100 feet in the south at Gwardalanga to 2,300 feet at the river, whence it rises in a series of irregular waves whose trend is parallel to the grain of the country until, at the nose of Kuh Dufarash, it stands at 3,800 feet. Two lobes extend beyond, both falling as irregularly shaped processes to about 3,000 feet. In some of the saddles between these earth waves ponds are still impounded and, in others, silts which collected in such ponds are left, the water having escaped by percolation.

To the northern limits of the sheet, where it rests on the Fars of Mishwand large, almost rectangular blocks of limestone continue to occur. One of these near the 3,800-foot high point on the nose of Kuh Dufarash measures 60 by 25 by 20 feet, and many of its neighbors are cuboidal in form with dimensions of the order of 20 feet (Fig. 3). The matrix here as elsewhere is composed of ungraded angular fragments down to the size of powder. The possibility of these blocks having originated from the flanks of Kuh Dufarash has been con-

FIG. 2.—General view of debris

sidered, but the sides of that mountain are smooth and regular and reveal no scar, change of nature, or shape where the boulder sheet impinges upon it. The great cubes are also found resting high upon the nose from which the gradient is so low that an angular mass could not have traveled down it. In the southern part occur blocks of the Eocene marly limestone reaching more than 300 feet in linear dimension and within themselves displaying normal bedding, but they grade down to smaller masses northward. Until the river gorge is crossed, the Eocene marly limestones compose most of the debris, but beyond it is made up almost entirely of Asmari limestone. The large size of the less resistant Eocene marly limestone blocks suggests that they were dragged forward under the sole of the main

slide and never moved with a velocity comparable to that of the Asmari limestone.

THE SCAR

The scar produced by the downfall of this material (Fig. 4) is bounded by two Asmari limestone cliffs, the eastern one rising to the peak of Filiman Kuh (7,300 ft.), and the western one to the tooth of Kuh Litanar (7,000 ft.). Kabir Kuh to the south has an altitude

FIG. 3.—Debris showing a 60-foot block 5 miles across the valley from the base of the scar. Note watch-tower built on a block to the right.

here of nearly 8,000 feet. This scar is just over 9 miles across and reveals a bared dip slope $2\frac{1}{2}$ miles wide. A minimum of 1,000 feet of rock has been removed to form the Asmari limestone part of the landslide, and, while the quantity of the marl group which has come away varies from about 500 feet downward, on an average about 1,300 feet of Asmari and marl group have fallen off. The volume of rock involved is therefore about 5 cubic miles or 20 cubic kilometers. Taking for this material the specific gravity of 2.5, it is merely a question of arithmetic to show that approximately 56,000 million long tons of rock have been involved in the catastrophe. The average height of the top of the range before the landslide occurred was

GEOLOGICAL MAP OF THE COUNTRY AFFECTED BY THE SAIDMARREH LANDSLIP.

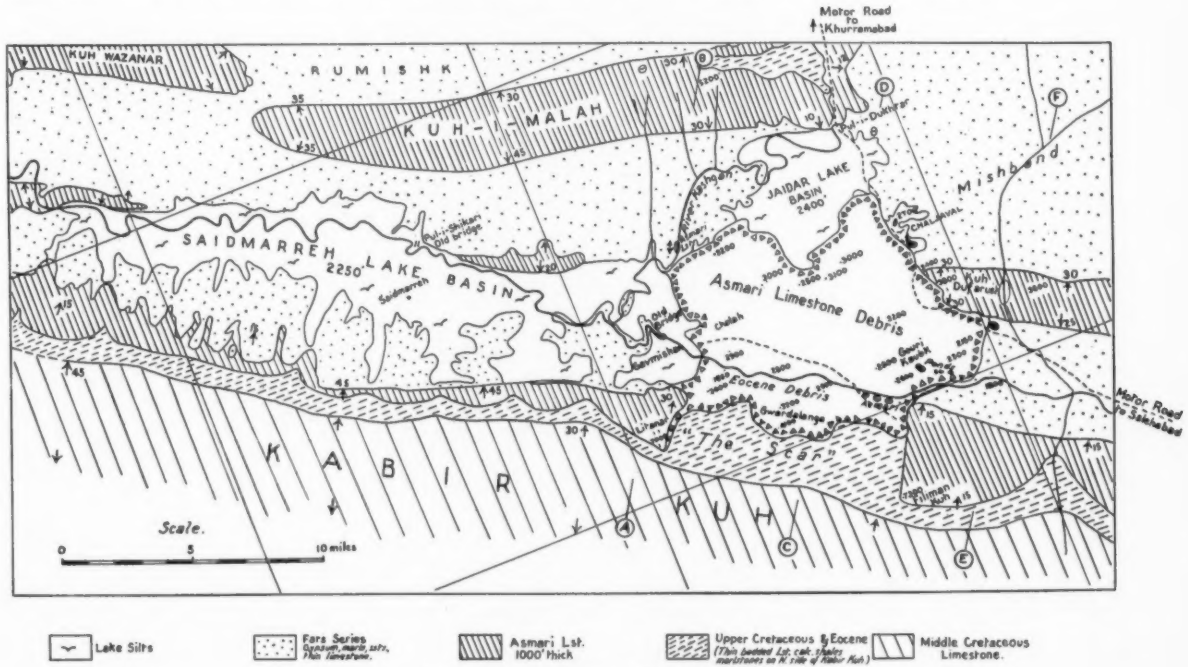

FIG. 4.—Geological map of the Saidmarreh

about 7,200 feet. The top of the Asmari limestone is exposed at the bottom of the scar at about 3,500 feet. The center of gravity of the mass was then at about 5,300 feet above sea-level. The height at which solid rock is encountered in the Saidmarreh gorge below the landslide is about 1,700–1,800 feet above sea-level, but only a small part of the material fell to this depth as the first part of the slip must

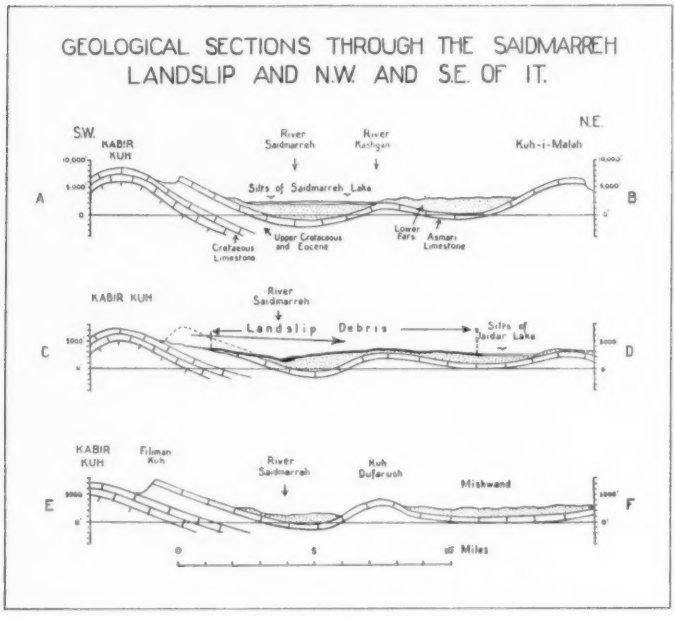

FIG. 5.—Sections

have filled in any irregularity of the valley floor, and it is estimated that a surface at about 2,300 feet is that to which the material on an average must have fallen—a drop of about 3,000 feet from the center of gravity (Fig. 5). The top part of the mountain which presumably came down last had to fall 4,900 feet and so would acquire greater momentum than an equal volume falling from the lower part of the mass. No doubt this was important because it gave the tail end of the fall impetus to shoot onward and upward by virtue of its

kinetic energy. The most northerly part of the debris probably originated in the most southerly part of the original sheet. From accounts of the Gohna landslip in 1893[2] and of the Quetta earthquake[3] in 1935 the fall was probably accompanied by great clouds of dust.

The flanking sierra of Kabir Kuh before the fall took place was made up of a regularly dipping sheet of limestone inclined toward the valley at from 15° to 25°. On most hills a coherent sheet of limestone in this attitude must be normally in a stable condition, for, when scree is found overlying the rock, it is in repose at even greater angles. Thus talus in chimneys on the sides of these limestone mountains is still encountered with slopes up to 30°. The Eocene in which gliding took place is often thin-bedded and composed of marly limestones and marls which are normally well compacted and not liable to form a slurry even when soaked. Still some abnormal lubrication appears to be needed to allow the slipping to commence upon an inclined plane with a dip of only 20°, and some unusual shake to start it moving.

THE MOVEMENT OF THE DEBRIS

Once the mass was set in motion, the rules of statics and ideal limiting values such as the angle of repose cease to apply. At the same time the sheet was starting to break up, and then both rotational motion and solifluction enter into play. The whole mass moving like a fluid can be pictured sending its main body forward against the obstructing Kuh Dufarash, while tongues of it shot up and across this hurdle rising 1,500 feet above the saddle just crossed below. No falling-off piecemeal could yield such an effect, for isolated masses endowed with linear and angular momentum rapidly disrupt under impact, and their reduced fragments have little capacity for travel. The composition of the whole trans-Saidmarreh mass is so uniform in its heterogeneity, great rectangular masses jostling with particles of dust from the riverside to the farthest lobe 7 miles away, that only a fluid turbulence could yield such a wide distribution with no tendency to grading of the constituent parts in the process or to

[2] Thomas H. Holland, "Report on the Gohna Landslip, Gahrwal," *Rec. Geol. Surv. India*, Vol. XXVII, Part II (1894), pp. 55–64.

[3] C. P. Skrine, "The Quetta Earthquake," *Geog. Jour*, Vol. LXXXVIII (1936), pp. 414–30.

rounding of their sharp edges. Thus may the presence of this mighty breccia slung out 9 miles from its source be explained, the great blocks having been carried on a raft which besides transporting them served to protect them from destruction.

It is, of course, not possible to decide what set the sheet of limestone in motion, but various causes may have helped. The region is one in which earthquakes occur, so that a seismic shock may have been the pressing of the trigger. The uncovered part of the valley shows that it had closely approached its present state of sculpture before the landslide because the old river terraces are covered by the detritus, and the present flood plain of the river seems to have been already established. It is reasonable to suppose that the rainfall was of the same order as that at present, which averages about 30 inches per annum but varies greatly from year to year. The rain comes down spasmodically and during exceptional storms as much as 6 inches falls in a day. Sometimes a succession of storms breaks in the course of a few days. Such rain would at least tend to provide lubrication in the marly limestone zone. The Asmari limestone rising in high ranges with slopes formed by dip surfaces occurs widely in the Zagros Ranges, and many times a wrinkling of the lower part of such a slope has been noted under the influence of gravity. Sometimes it is a kind of buckling or bulging, an incipient knee fold, sometimes a cascade where there is more than one bulge.[4] If such a secondary fold had formed here by the slipping-down of the massive limestone over the marly beds under the influence of its own weight, a local steepening of the dip would be produced such as has often been seen elsewhere, and this would have facilitated initiation of the slide which ended in the catastrophe. All three causes probably played a part in setting things going. The slide seems to have occurred as a single incident as there is no evidence of successive sheets in the apron of debris.

The seat from which the rock body slipped exposes the marls which have since been dissected by a multitude of rills with their courses separated by steep ridges and is now characterized by badland topography not deeply etched (Fig. 6).

[4] J. V. Harrison and N. L. Falcon, "Collapse Structures," *Geol. Mag.*, Vol. LXXI (1934), pp. 529–39.

FIG. 6.—Saidmarreh landslip and scar

LAKES DAMMED BY THE LANDSLIP

For a distance of 24 miles west-northwest of the landslip the old valley of the Saidmarreh River is filled by a flat-topped sheet of bedded sands and silts. It is about 100 feet thick at the northwestern end and about 400 feet thick at the southeastern. Its level maintains a height of about 2,250 feet above sea-level from end to end, and the old lateral valleys, cut into the Fars veneer of the syncline, have been filled up to this contour. The deposit is the result of silting up a lake formed by the damming of the Saidmarreh River by the landslide, a process which probably took place fairly rapidly on account of the heavy load of sediment carried by the river each spring. At about 2,300 feet the water overflowed and cut down through the fallen material forming the Gwardalanga gorge, about 12 miles long. Before this had reached the upstream sill of the obstruction, the upper Saidmarreh had already established meanders across the mud flats of the lake, and, with the lowering of the sill, these became entrenched as one finds them today.

The Kashgan River from the north was also blocked by the front of the landslip and formed the Jaidar Lake, roughly circular in outline at about 2,400 feet above sea-level. The prelandslip river emerged from Pul-i-Dukhtar gorge and seems to have flowed in a south-southwesterly direction to join the Saidmarreh. The present river, however, turns sharply west below Pul-i-Dukhtar and flows in entrenched meanders across the lake beds to enter a gorge cut in the solid Fars Series for nearly 10 miles before debouching into the "Saidmarreh Lake." The waters of Jaidar Lake, therefore, overflowed across a col on an old spur into the bed of one of the little tributaries from the slopes of Kuh-i-Malah. It crosses the "Saidmarreh Lake" following a meandering course to join the Saidmarreh River at Gavmishan.

On the northeastern front of the debris water from minor drainage on the northern side of Kuh Dufarash collected at 2,700 feet. A small body of water still lies here, but most of it has escaped by seepage, there being no surface outlet. Other small ponds developed between the slopes of Kuh Dufarash and the landslide but are now represented only by small deposits of silt.

THE AGE

The landslip took place recently from the geological point of view, for the debris has moved across the old terraces and the plain of the lower Saidmarreh River. It is prehistoric, however, because a ruined town built in pre-Sassanian times stands upon the silts of the "Saidmarreh Lake." The Saidmarreh River had entrenched itself down to bedrock by Sassanian times since the old bridge at Gavmishan has its foundation upon the Fars, and these are still awash showing that little erosion of the river bed has taken place during the last two thousand years. Upstream some changing in the river's course has occurred because the Sassanian bridge, Pul-i-Shikari, has been stranded a few hundred yards away from the present bed of the river. We know therefore that the fall took place much more than two thousand years ago.

DISCUSSION

Large landslides appear to be comparatively rare, although submarine slumping on a large scale is now invoked by certain authorities[5] to explain contorted strata and sheets of coarse breccia interbedded with more normal deposits. No comprehensive search through the scattered and voluminous literature on the subject has been attempted, and no American landslide can be cited for comparison, although as large or larger examples may occur in the Cordillera. In Europe the largest example described took place in an interglacial stage in Switzerland (Fig. 7).[6] From a sheet of Malm limestone dipping gently toward the Rhine Valley above Flims 3 cubic miles of rock fell off in a single catastrophe. This has been spread out for a distance of nearly 10 miles along the valley from Reichenau to Sagens and covers an area of 16 square miles. Its age is known, since the debris overlies moraine at one place but has itself

[5] E. B. Bailey and J. Weir, "Submarine Faulting in Kimmeridgian Times, East Sutherland," *Trans. Roy. Soc. Edin.*, Vol. LVII (1933), pp. 429–67; E. B. Bailey, L. W. Collet, and R. M. Field, "Palaeozoic Submarine Landslips near Quebec City," *Jour. Geol.*, Vol. XXXVI (1929), pp. 577–614; O. T. Jones, "On the Sliding or Slumping of Submarine Sediments in Denbigshire, North Wales, during the Ludlow Period," *Quart. Jour. Geol. Soc. London*, Vol. XCIII (1937), pp. 241–83.

[6] Albert Heim, *Geologie der Schweiz* (Basel, 1920), II, 309–401.

been sprinkled with erratics during a later glaciation. The height from the top of the scar to the original valley floor is 6,500 feet. The largest landslide of recent times occurred at D'Ousoï in the Pamirs on February 18, 1911,[7] when approximately half a cubic mile of rock fell into the valley of the Murgab (Fig. 7). The material was

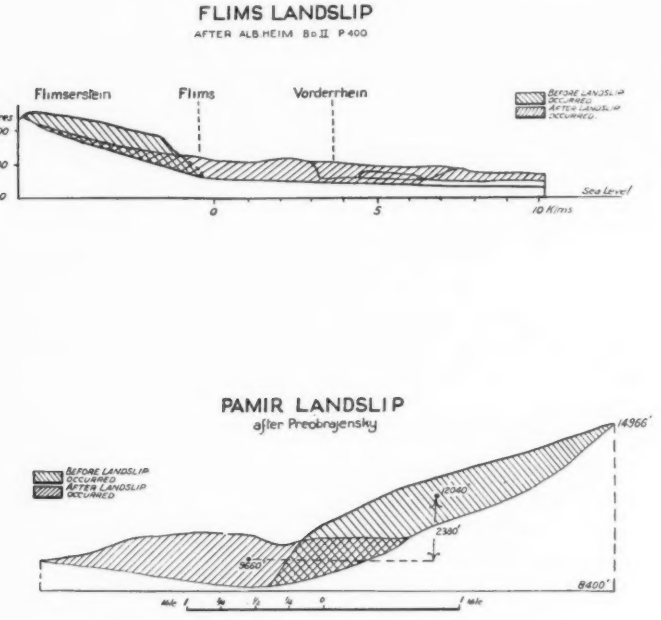

FIG. 7.—Cross sections after Heim and Preobrajensky

distributed over 4 square miles of the valley bottom in which by 1915 it had held up a lake 1,155 feet deep. From the top of the scar to the original valley bottom the difference in height is approximate-

[7] J. Preobrajensky, "Eboulement d'Ousoï (Pamir)," *Comité géologique matériaux pour la géologie générale et appliquée*, Vol. XIV (Petrograd, 1920), pp. 1–21, Pl. 9; "On the Cause of the Landslide in the Pamirs in 1911," Minor Notes (*Geologicheski Vystnik*), Vol. I, No. 4 (1915), pp. 238–43. We are indebted to Dr. Lockhart for a translation of this paper.

ly 3,800 feet. It is stated that the center of gravity was moved down 2,380 feet. Table 1 affords a dimension of these three large landslides for easy comparison.

TABLE 1

	Locality		
	Saidmarreh	Flims	D'Ousoï
Volume	5 cu.mi.	3 cu.mi.	0.5 cu.mi.
Area	64 sq.mi.	16 sq.mi.	4 sq.mi.
Drop	3,000 ft.	*ca.* 4,000 ft.	2,380 ft.
Maximum height	5,400 ft.	6,500 ft.	3,800 ft.
Date	Subrecent	Interglacial	Feb. 18, 1911

Even if the Saidmarreh landslip proves to establish no record in point of size, it remains a notable phenomenon on account of the extraordinary distribution of the fallen material. This has traveled 9 miles forward from the slopes off which it fell and, in doing so, has not only crossed a large valley but has ridden up more than 1,500 feet over a range and carried on into the valley beyond.

RELATIONS BETWEEN WALL ROCK AND INTRUSIVES IN THE CRYSTALLINE COMPLEX OF THE SOUTHERN SIERRA NEVADA OF CALIFORNIA

ROBERT W. WEBB
University of California at Los Angeles

ABSTRACT

The crystalline complex of the southern Sierra Nevada is composed of remnants of rocks of Calaveras (?) age or older, which were intruded by gabbros, quartz-diorites, and granodiorites. The remnants of older rocks are irregular and septa-shaped residuals. The relations of the crystalline units are discussed, and the thesis advanced that deformation of the older rocks was practically completed by the time of invasion of the magmatic units. The central Sierra, where studied by Mayo and Erwin, is compared and contrasted in petrologic condition with the southern Sierra Nevada.

INTRODUCTION

Studies of the plutonic rocks of the southern Sierra Nevada of California and their relations to older rocks have been carried on by the writer since 1933. It is the purpose of this paper to record some of the results of this study, and to compare and contrast this region with those to the north, which have been studied chiefly by Knopf,[1] Mayo,[2] and Erwin.[3]

LOCATION AND PHYSICAL FEATURES

The district under consideration lies in Tulare, Kern, and Inyo counties in the central and eastern part of the southern Sierra Nevada, in the Kernville quadrangle. Detailed mapping of more than 600 square miles was completed, and reconnaissance on an additional 400 square miles was undertaken.

[1] Adolph Knopf, "A Geologic Reconnaissance of the Inyo Range and Eastern Slope of the Southern Sierra Nevada, California," *U.S. Geol. Surv. Prof. Paper 110* (1918).

[2] Evans B. Mayo, "Some Intrusions and Their Wall Rocks in the Sierra Nevada," *Jour. Geol.*, Vol. XLIII (1935), pp. 673–89; "Sierra Nevada Pluton and Crustal Movement," *ibid.*, Vol. XLV (1937), pp. 169–92.

[3] Homer D. Erwin, "Geology and Mineral Resources of Northeastern Madera County, California," *Calif. Jour. Mines and Geol.*, Vol. XXX (1934), pp. 7–78; "Mesozoic Geology of the Ritter Region, Sierra Nevada, California," *Jour. Geol.*, Vol. XLV (1937), pp. 391–413.

The southern Sierra, as suggested by Hake[4] and later emphasized by Miller,[5] is a broad platform bounded by faults along the Owens Valley on the east and the San Joaquin Valley on the west. Internally the mass is broken by the major Kern Canyon fault,[6] and minor faults which become more numerous to the south in the vicinity of Tehachapi, California.[7] Transecting the region from east to west is the distinctive canyon of the South Fork of the Kern River, a physiographic anomaly of unusual interest. The average elevation of the interior platform of this large horst block is about 7,500 feet, sloping gently from north to south, flattening somewhat south of the South Fork Valley of the Kern, where an elevation of 5,000–5,500 feet is reached. The platform is dissected by small streams running in V-shaped canyons, typifying early to middle youth. The main fork of the Kern River (sometimes called north fork) has carved its valley adjacent to the Kern Canyon fault along which less resistant rocks outcrop. The major platform is thus divided by what appears to be a large sunken block, made up, in the Kernville region, chiefly of the older metamorphic rocks. The steep eastern front of the southern Sierran platform is the eroded scarp of the Sierran fault, rising nearly 4,000 feet above the floor of Owens-Indian Wells Valley; the western front of the platform descends through a series of "stepped-down blocks," each successively lower than the preceding, which are separated by a series of faults of small individual displacement but large total displacement.

PREVIOUS PETROLOGIC STUDY

The southern Sierra Nevada has received far less attention geologically than any other part of the Sierra. Lawson[8] in his paper on

[4] Benjamin F. Hake, "Scarps of the Southwestern Sierra Nevada, California," *Bull. Geol. Soc. Amer.*, Vol. XXXIX (1928), pp. 1017–30.

[5] William J. Miller, "Geologic Sections across the Southern Sierra Nevada of California," *Univ. Calif. Dept. Geol. Bull. 20* (1931), pp. 331–60.

[6] Robert W. Webb, "Kern Canyon Fault, Southern Sierra Nevada," *Jour. Geol.*, Vol. XLIV (1936), pp. 631–38.

[7] A. C. Lawson, "The Geomorphogeny of the Tehachapi Valley System," *Univ. Calif. Dept. Geol. Bull. 4* (1906), pp. 431–62; J. P. Buwalda, "Structure of the Southern Sierra Nevada," *Bull. Geol. Soc. Amer.*, Vol. XXV (1915), p. 403; "Fault System at the Southern End of the Sierra Nevada, California," *ibid.*, Vol. XXXI (1920), p. 127.

[8] "The Geomorphogeny of the Upper Kern Basin," *Univ. Calif. Dept. Geol. Bull. 3* (1904), pp. 291–376.

the Upper Kern Basin discussed the geomorphic setting of the area north of the one under consideration, and extended his observations southward in a second paper[9] on the Middle Kern. These papers contained little reference to the petrology; in the first one Knopf[10] reported petrographically on some hand specimens collected by Lawson in the Upper Kern. Miller[11] presented a geologic map, with accompanying petrologic data, across the southern Sierra, including part of the region studied by the writer.

GEOLOGIC SETTING

METAMORPHIC ROCKS

Kernville series.—The metamorphic rocks belong to the Kernville series, a name proposed by Miller[12] for the meta-sedimentary formations exposed in the vicinity of Kernville, California. The Kernville series is composed of quartzite, phyllite, mica schist, and marble, with less than 2 per cent of metamorphosed pyroclastics and rolled gneiss. Quartzite predominates in the series, comprising a higher percentage than all other types, based on the thickness of the beds. Lithologically, the series suggests the Calaveras formation of the Sierran foothills to the north, and this correlation has already been suggested.[13] The absence of recognizable fossils, even where the rocks are only moderately metamorphosed, suggests that these units may belong to an earlier period of sedimentation, even pre-Cambrian; they bear no lithologic similarity to those beds considered by Mayo[14] to be Devonian, in an adjacent region to the north, and are more completely metamorphosed. Only one metamorphic unit can be defined in this area. No evidence of two distinct series has been found. This differs from the regions to the north, where Mayo[15] has discovered metamorphic units of the Paleozoic and Mesozoic eras.

[9] Lawson, "The Geomorphic Features of the Middle Kern," *Univ. Calif. Dept. Geol. Bull. 4* (1906), pp. 397–409.

[10] In Lawson, *op. cit.* (1904).

[11] *Loc. cit.* [12] *Ibid.*, p. 335. [13] *Ibid.*, p. 342.

[14] "Fossils from the Eastern Flank of the Sierra Nevada, California," *Science*, Vol. LXXIV (1931), pp. 514–15.

[15] "Some Intrusions and Their Wall Rocks in the Sierra Nevada," *loc. cit.*

PLUTONIC ROCKS

The plutonic units in the composite Sierran batholith include three separate intrusive groups. The earliest of these is a gabbro, which, after emplacement in small batholithic and stocklike masses, was followed closely by a quartz-diorite. These comprise the first intrusion period in the geologic history. Following their emplacement, the main intrusive group of the Sierra invaded the older rocks, with the resultant emplacement of a silicic mass varying in composition from alaskite through quartz-monzonite to granodiorite. This group in the Kernville region has been called the Isabella granodiorite by Miller.[16]

Gabbro.—The gabbro is typically medium- to fine-grained, with occasional coarse-grained facies. Its composition as determined by volume per cent from thin sections is An_{70}–An_{80}, 80 per cent; hornblende, commonly altered to epidote, 18 per cent; and pyrite, 2 per cent. Post-consolidation alteration is indicated by epidote, chlorite, sericite, and calcite, the latter two on the plagioclase and the former on the hornblende. Fracture veinlets crossing grain boundaries are filled with quartz. Alteration is also prominent along grain boundaries. Pyrite and occasional grains of magnetite surround other minerals; they are secondary. All minerals show evidence of strain. Undulatory extinction in the feldspars and bent cleavages both in the feldspars and in the hornblende are common. The rock has hypidiomorphic texture, with cataclastic (even mortar) textures in some grain combinations.

Quartz-diorite.—The quartz-diorite is a melanocratic rock of medium to fine grain, with equigranular texture. Its facies vary from a hornblende-diorite and biotite-hornblende-quartz-diorite to microcline-quartz-diorite. The average carries An_{40}, 68 per cent; quartz, 12 per cent; orthoclase or microcline or both, 5 per cent; hornblende, 10 per cent; biotite, 3 per cent; apatite, sphene, magnetite, and ilmenite, 2 per cent. Alteration produces leucoxene from both the ilmenite and the sphene; epidote and sericite from the plagioclase; a little kaolinite from the potash feldspars; and occasional oxides of iron. There is some textural indication of the secondary intro-

[16] *Op. cit.*, p. 344.

duction of sphene. The plagioclase is zoned, with selective alteration becoming more intense toward the core.

Isabella granodiorite.—In the area of detailed study the usual composition of the Isabella unit is a quartz-monzonite. It seems best, however, to retain the designation "Isabella granodiorite" since this is the average composition in the entire southern Sierra Nevada. An average volumetric composition of the Isabella, which is medium- to coarse-grained leucocratic, is: quartz, 30 per cent; orthoclase and/or microcline, 30 per cent; An_{30}–An_{40}, 30 per cent. Accessory minerals vary from zero to 10 per cent, usually considerably less than the latter. Common varietal and accessory minerals are biotite, hornblende, muscovite, apatite, sphene, and magnetite. Kaolinite, sericite, epidote, hematite, and occasionally chlorite are found. Sphene is abundant in some facies. The Isabella is the last intrusive group and seems to have been emplaced considerably later than the diorite-gabbro groups. The Isabella is considered late Jurassic or early Cretaceous by Miller.[17] Further evidence for the age of Sierran silicic intrusives has recently been presented by Hinds.[18]

Other rocks.—Volcanic sequences capping older groups and some alluvial deposits constitute the remaining petrologic units.

SHAPES AND ATTITUDES OF KERNVILLE REMNANTS

The remnants of the Kernville series are divisible into two types: (1) those of mixed rock type and random shape, with irregular dimensions, but usually nearly equidimensional, and (2) those of septal shape which are composed, usually 95 per cent or more, of the one metamorphic type—quartzite. Remnants of the second type are commonest within the Isabella formation, while those of the first type separate members of different invasive units (e.g., gabbro- and quartz-diorite). Data regarding mode of emplacement are obtainable chiefly from the septa-like inclusions. Two large septa were studied in detail in the Kernville area, one having dimensions approximately 6 miles long and $\frac{1}{8}$ mile wide; the other, about 3 miles

[17] *Ibid.*, p. 351.

[18] N. E. A. Hinds, "The Jurassic Age of the Last Granitoid Intrusives in the Klamath Mountains and Sierra Nevada, California," *Amer. Jour. Sci.*, Vol. XXVII (1934), pp. 182–92.

long and about 500 feet wide. Several smaller septa are found in the same area.

Similar features are noted to the north by Mayo,[19] who further calls attention to the elongate character of granitic rock masses separating the septa of the older rocks. The geologic map presented by Knopf[20] also shows septa of the older rocks in the region intervening between that studied by Mayo and that here described.

The significant difference between the septa described by other workers and those of the Kernville region lies in the composition of the rocks comprising them. In the regions to the north such septa show little difference in composition from other inclusions associated with them, which lack the septal shape. In the Kernville area those masses of septal shape are always composed of quartzite, never associated with another metamorphic type. Such septa always stand nearly vertical with what seem to be vertical contacts. However, nowhere were found areas in which the downward extent of the septa could be seen, such as Knopf and Thelen,[21] Knopf,[22] Erwin,[23] and Mayo[24] found in adjacent regions. The attitude of the contacts agrees closely with those described by Mayo,[25] but the writer found no exceptions to the rule of high-angle contacts.

The two types of roof remnants reflect the regional trends of the Sierra, namely, N. 30° W.—N. 40° W., with high-angle dips, never less than 60°. Regional attitudes do not differ in units of different shape. The total lack of low dips contrasts with the northern area, where Mayo[26] found low-angle dips to be present, especially in small folds recognizable in the metamorphic units.

THE KERNVILLE SERIES AND FORCE OF EMPLACEMENT

There has been considerable discussion in the literature as to the attitude of the meta-sedimentary rocks of the Sierra Nevada before

[19] "Some Intrusions and Their Wall Rocks in the Sierra Nevada," *op. cit.*, p. 680.

[20] *Loc. cit.*

[21] Adolph Knopf and P. Thelen, "Sketch of the Geology of Mineral King, California," *Univ. Calif. Dept. Geol. Bull.* 4 (1906), pp. 227–62.

[22] *Loc. cit.* [23] *Loc. cit.*

[24] "Some Intrusions and Their Wall Rocks in the Sierra Nevada," *loc. cit.*

[25] *Ibid.* [26] *Ibid.*

the invasion of the batholiths. Where two meta-sedimentary units are found together, it has been definitely shown by earlier workers[27] that the older (Calaveras) unit is more highly metamorphosed and folded than the younger (Mariposa). In the Kernville region only one meta-sedimentary unit is present, which, it has been suggested, is the Calaveras unit or older. Knopf and Thelen,[28] Lawson,[29] and others have indicated their belief that the southern Sierra has been more completely unroofed by erosion than have other parts of the Sierra, and thus that evidence of the position of the old rocks during intrusion is fragmentary. Key beds, if present, would not be likely to be found in units as small as those of septal form, and careful search in other remnants in the Kernville region has failed to reveal any beds by which folding might be determined.

In the Kernville region, however, it seems that deformation had reached an advanced stage before emplacement of the gabbro and quartz-diorite intrusions. In one case the flow structure of a small stock of quartz-diorite and associated gabbro is molded to encircling wall-rock bedding and foliation. Cleavage and bedding are essentially parallel, and they follow faithfully the curving trend of the igneous contact. Obviously both bedding and cleavage are pre-intrusion structures, bent to fit the form of the stock. Had major deformation continued after emplacement of all intrusions, granulation or foliation in invading rocks would transect wall-rock structures where they wrap around such stocks. Bedding and foliation would not remain essentially parallel through all changes of trend, and not all wall-rock structure would so perfectly fit the forms of intrusions. That deformation of the Kernville series was not entirely complete by the time of the gabbro and quartz-diorite invasion is shown by the evidence of some metamorphism in these intrusives since their emplacement, namely: mortar textures and other cataclastic effects; vein fillings of later minerals in gash fractures; and sheared and granulated zones which are all post-consolidation effects. Cataclastic effects have not been observed in the Isabella unit,

[27] Summarized in François E. Matthes, "Geography and Geology of the Sierra Nevada," *Guidebook 16, Internatl. Geol. Cong., XVI Sess.* (1933), pp. 26–40.

[28] *Loc. cit.*

[29] "The Geomorphogeny of the Upper Kern Basin," *op. cit.*

which may indicate completed or nearly completed deformation of the older rocks by the time of the Isabella invasion.

W. J. Miller,[30] in his study of the region slightly south of that covered by the detailed work of the writer, says:

> The facts that the bedding and foliation of the Kernville series are parallel, that the dips are all rather uniformly steep, that the strike of the beds in the remnants of the once very extensive Kernville series is almost uniform, that the great body of granodiorite which invaded the series is generally very massive and non-foliated except near contacts where it often has been changed to mica schist, all strongly point to the conclusion that the Kernville series had been highly (probably isoclinally) folded before the granodiorite magma intruded it.

In the area examined by Miller, septa-like masses of the Kernville series were not present. Even in such small masses the attitudes are persistent. Furthermore, it is notable that small masses adjacent to large areas of the Kernville series maintain the attitude of the parent-mass even when a considerable distance away. Inclusions with dimensions 20 feet long by 2 feet wide, with unknown depth, though separated by $\frac{1}{8}$–$\frac{1}{4}$ mile from the parent-mass, have the attitude of the parent. Control of intrusive by wall rock is certainly indicated by this fact; otherwise, rotation of these small masses would be expected, with corresponding divergence from regional attitudes. Crude foliation in the Isabella granodiorite is defined by coarse, gray quartz grains, marginal to wall rocks, in which flowage is parallel to wall-rock bedding and foliation.

In addition, support for the hypothesis requiring deformation far advanced before the Isabella granodiorite intrusion is offered by (1) the lack of cross-cutting relations between intrusive and wall rock which would generally not be the case were the wall rocks deformed and ruptured during invasion. There is even some evidence to suggest that the magma followed the surface of one of the quartzite layers of a septum, and, controlled by this plane, migrated upward; (2) the fact that thrust planes in the Kernville series are lacking in this region while they have been found to the north by Erwin.[31] He attributes them to the thrusting action of the granodiorite in-

[30] *Loc. cit.*

[31] "Geology and Mineral Resources of Northeastern Madera County, California," *loc. cit.*; "Mesozoic Geology of the Ritter Region, Sierra Nevada, California," *loc. cit.*

trusion upon its rise into the crust. Their absence probably indicates lack of force on the part of the magma during invasion, and thus deformation completed before intrusion.

LACK OF VISIBLE EVIDENCE OF ASSIMILATION DURING EMPLACEMENT

It was first thought that the batholithic units of the Isabella formation occupied the areas they do because selective assimilation of the Kernville series had taken place. Where the remnants are all quartzite and highly siliceous they may have resisted attack by a siliceous magma, while the argillaceous and calcareous members were assimilated. If such were the case, the channelways of migration of the magma were produced by assimilation of zones favorable toward reaction with the magma.

To this hypothesis objections were at once apparent. First, it seemed unlikely that all the material of composition other than quartzite would be assimilated. Second, the quantity of material involved, if one can judge by the quantities present elsewhere in the series, would make it inevitable that the magma show strong evidence of introduction of material of new composition. Careful petrographic analyses of rocks adjacent to well-exposed contacts with the quartzite inclusions were made. At one particularly typical and well-exposed contact it was found from a sharp boundary, over a distance of less than 200 yards, that the adjacent granodiorite changed composition only by the increase in the percentage of sphene in the rock. The normal facies carried $\frac{1}{2}$–1 per cent sphene; varying progressively in size and amount, becoming coarser toward the contact, the sphene increased to as high as 8 per cent. Otherwise, evidence for the introduction of material was lacking. Further, where small detached masses of the invaded rock occur, no composition changes are observed in the intrusive, even where widely separated from the main inclusion. Petrographic analyses of numerous slides of specimens from widely separated parts of the Isabella unit show that the rock is essentially the same in composition whether adjacent to or separated from remnants of the Kernville series. The assimilation hypothesis is, therefore, not supported by the observations.

Lack of evidence for assimilation in regions to the north was mentioned by Mayo,[32] who discarded the hypothesis that these processes contributed materially in emplacement.

FORCE OF EMPLACEMENT IN ADJACENT REGIONS

Mayo[33] finds support for the theory that the magma rose under great pressure in the region to the north, where he presents adequate evidence to show that crushing effects were severe on the invaded rocks. This is interpreted (with other evidence) as indicating forceful emplacement of the intrusions. However, he believes that the invaded rocks were almost completely deformed before the invasion of the main batholith. In the Kernville area the writer finds little evidence of forceful emplacement. However, it has been stated that erosion of the southern Sierra has been much deeper than in other parts of the range. Thus it might be expected that small remnants of wall rocks, in what was during intrusion a central or lower part of the intrusion chamber, might fail to show evidence of forceful emplacement on the part of the magma, and that at equivalent levels of intrusion the magma may have advanced under deforming pressure here as well as to the north.

SUMMARY

From evidence presented it appears that the magmatic units of the southern Sierra entered rocks already intensely deformed, and that deforming forces had practically ceased to operate at the time of intrusion. At the level of erosion represented in the Kernville region, active thrust on the part of the magma during intrusion is not indicated. A quiet invasion under hydrostatic rather than orogenic pressure is evidenced by the elongate, nonruptured septa-like inclusions of the Kernville series. At a higher level in the batholith, such as is found northward, activation of the magma under intense pressure is definitely known. In all probability, similar features to those found in the Kernville area would be found to the north at a comparable depth.

At high levels active thrust during emplacement, with pressure

[32] "Some Intrusions and Their Wall Rocks in the Sierra Nevada," *loc. cit.*

[33] *Ibid.*, p. 687.

decreasingly effective downward in the advancing magma, is indicated for the composite batholith of the Sierra in the areas considered.

In the areas of the central Sierra, where studied by Mayo and Erwin, there are found (1) gentler dips in the metamorphic units; (2) widespread cataclastic effects; (3) thrust faults in wall rocks, attributed to the forceful invasion of the intrusive; (4) complex folding so that attitudes vary from regional trends; and (5) increased metamorphism near contacts with igneous bodies. These features are almost entirely absent from the southern Sierra where studied by the writer.

In the Kernville area there are (1) large septa-like inclusions composed entirely of quartzite; (2) no meta-volcanic rocks in any of the Kernville units comparable to those to the north; (3) no small intrusions which reflect regional trends of the range itself; (4) regular attitudes of older rocks with notable absence of minor folds; and (5) evidences of thermal metamorphism in wall rocks.

In both areas one finds (1) similarity in sequence of intrusions; (2) similarity in shape of many of the wall-rock residuals; (3) lack of major assimilation; and (4) typically sharp, high-angle contacts between wall rock and intrusive.

ACKNOWLEDGMENTS.—The writer especially wishes to thank Dr. Evans B. Mayo, whose works are frequently cited in this paper, for reading the manuscript and for the excellent summary of his work which he presented at a meeting of the Branner Geological Club of Southern California, on May 21, 1937, which was of indispensable aid in the preparation of this paper. Dr. William J. Miller, professor of geology, University of California at Los Angeles, suggested the study of the Kernville area, aided the writer in the field, and read the manuscript. Dr. George H. Anderson of the same institution also read the manuscript. At the California Institute of Technology, Dr. Ian Campbell, associate professor of petrology, under whom the investigations were conducted while the writer was a student in the Balch Graduate School of the Geological Sciences, aided in the field and in preparation of the manuscript; Mr. Robert P. Bryson worked with the writer in the field during two seasons. These services are all gratefully acknowledged.

THE FORD RIVER GRANITE OF THE SOUTHERN COMPLEX OF UPPER MICHIGAN

R. M. DICKEY
Michigan College of Mining and Technology

ABSTRACT

A granite-porphyry which comprises most of the Southern Complex of the upper peninsula of Michigan and which has been variously considered Laurentian or post-Huronian is indicated by interpretation of field evidence to be post-Lower Huronian and pre-Middle Huronian in age. It is named the Ford River granite. The possibility is suggested that this granite may be a correlative of the Algoman granites of the north shore of Lake Superior.

INTRODUCTION

Renewed inquiry into the relative age of the igneous and metamorphic rocks of a large area south of the Marquette synclinorium and of the Huronian rocks which border it on the north, south, and west was initiated in 1931 by Lamey with the first of a series of five articles.[1] A major conclusion reached in these papers is that the area, known either as the Southern Complex or as the Republic granite, is dominantly composed of post-Huronian granite.

The writer entered the discussion in 1936 with a paper[2] which concluded that granites of three distinct ages are present in the Southern Complex; two of these were stated to be Laurentian, and the third, of minor areal extent, to be post-Huronian.

Lamey and the writer are in complete agreement that post-Huronian granite occurs in the district and, further, that Laurentian granite is also to be found. The point of major dispute is the age of a granite-porphyry which evidently makes up by far the largest portion of the complex.

[1] C. A. Lamey, "Granite Intrusions in the Huronian Formations of Northern Michigan," *Jour. Geol.*, Vol. XXXIX (1931), pp. 288–95; "The Intrusive Relations of the Republic Granite," *ibid.*, Vol. XLI (1933), pp. 487–500; "Some Metamorphic Effects of the Republic Granite," *ibid.*, Vol. XLII (1934), pp. 248–63; "The Palmer Gneiss," *Bull. Geol. Soc. Amer.* Vol. XLVI (1935), pp. 1137–61; and "Republic Granite or Basement Complex?" *Jour. Geol.*, Vol. XLV (1937), pp. 487–510.

[2] "The Granitic Sequence in the Southern Complex of Upper Michigan," *Jour. Geol.* Vol. XLIV (1936), pp. 317–40.

In the writer's paper[3] much stress was put upon the assumption that the Huronian rocks of the region had experienced only one major period of orogeny. It was shown that the granite-porphyry, as well as basic dikes intruding it, had been subjected to deformation subsequent to their complete solidification, and that the post-Huronian granite offers no evidence of such deformation. This was, in the writer's opinion, sufficient to remove the two granites from the category of phases of the same intrusion, and since no major period of mountain-building was known to have taken place in Huronian time, the granite-porphyry was regarded as Laurentian. This conclusion was supported by occurrences of Huronian conglomerates overlying the granite-porphyry.

During the summer of 1937 the writer, having an opportunity to re-examine the question of the age of the granite-porphyry, found a series of outcrops which seem to indicate, when considered in relation to other field evidence, that the granite-porphyry of the Southern Complex is neither Laurentian nor post-Huronian, but is post–Lower Huronian and pre–Middle Huronian in age. The so-called Lower Huronian and Middle Huronian of this part of Upper Michigan are apparently separated by a tremendous orogenic disturbance and major granitic intrusion.

THE FLOODWOOD EXPOSURES

In portions of Sections 19, 20, 29, and 30, T. 44 N., R. 29 W., in Upper Michigan, occurs a series of granitic exposures which trend roughly west of north, and are here called the Floodwood exposures, because Floodwood is the nearest railroad siding ordinarily indicated on maps of the area. The outcrops are reached by turning east from State Highway 95 at the north end of Silver Lake, and following a trail generally eastward for a distance of approximately 2 miles. Near the north end of this line of exposures the trail turns to the south, but several trails branch eastward from it and cross the trend of the outcrops.

The general location of the area, with respect to the Southern Complex, is shown on the accompanying map (Fig. 1), and the exposures (located by use of a plane table and telescopic alidade) are

[3] *Ibid.*

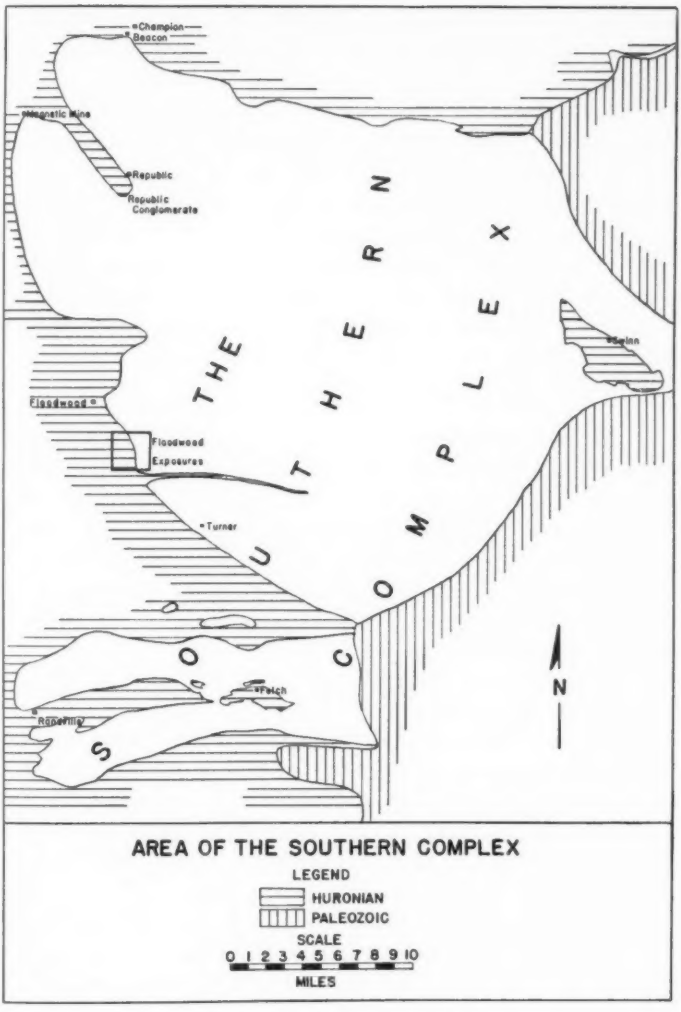

FIG. 1.—The Southern Complex

indicated in Figure 2. A few outcrops of granite-porphyry occur to the north and east of the northernmost outcrop shown, but these have no special bearing upon the following discussion.

For convenience the exposures are divided into three portions, principally with regard to the igneous material present: a northern area of granite-porphyry with minor amounts of pegmatite and quartzite "ghosts";[4] an intermediate area of medium-grained granite, aplite, pegmatite, and quartzite "ghosts"; and a southern area of pegmatite and abundant remnants of intruded quartzite. Furthermore, although in each of these divisions the exposures are numerous, the areas are separated by distances of about 1,000 feet and 1,500 feet, respectively, in which outcrops are absent.

DESCRIPTIONS OF EXPOSURES BY AREAS

The Floodwood outcrops occupy a narrow, curving area of about 2 miles in length, measured along the arc. The curve trends northwest in the northern part and swings to the west in its southern portion, where it occupies a north-south line. The west side of the arc is bordered by sand plains, while to the east of the exposures cutover swamp is common. In two instances well-marked swampy areas separate the exposures. Near the south end is a small pond which has been dammed by beaver.

All the outcrops show varying degrees of rounding and scouring by glaciation; this, together with a general lack of heavy vegetation and soil cover on the surfaces of the outcrops, has resulted in remarkably clear exposures of many of the contacts.

The northern area.—Granite-porphyry is by far the most common igneous rock in the northern area. It consists of prominent phenocrysts of orthoclase and microcline, often 2 inches or more in maximum dimension and usually showing a parallel alinement, in a matrix of glassy to opalescent quartz, biotite, and acid plagioclase. Carlsbad twinning is characteristic of the orthoclase phenocrysts. The rock is ordinarily gray, but may assume a decidedly pink coloration. The feldspar alinement here is about east-west for the most part, but deviates locally from this position by as much as 30° north or south.

[4] J. T. Stark, "Migmatites of the Sawatch Range, Colorado," *Jour. Geol.*, Vol. XLIII (1935), p. 13.

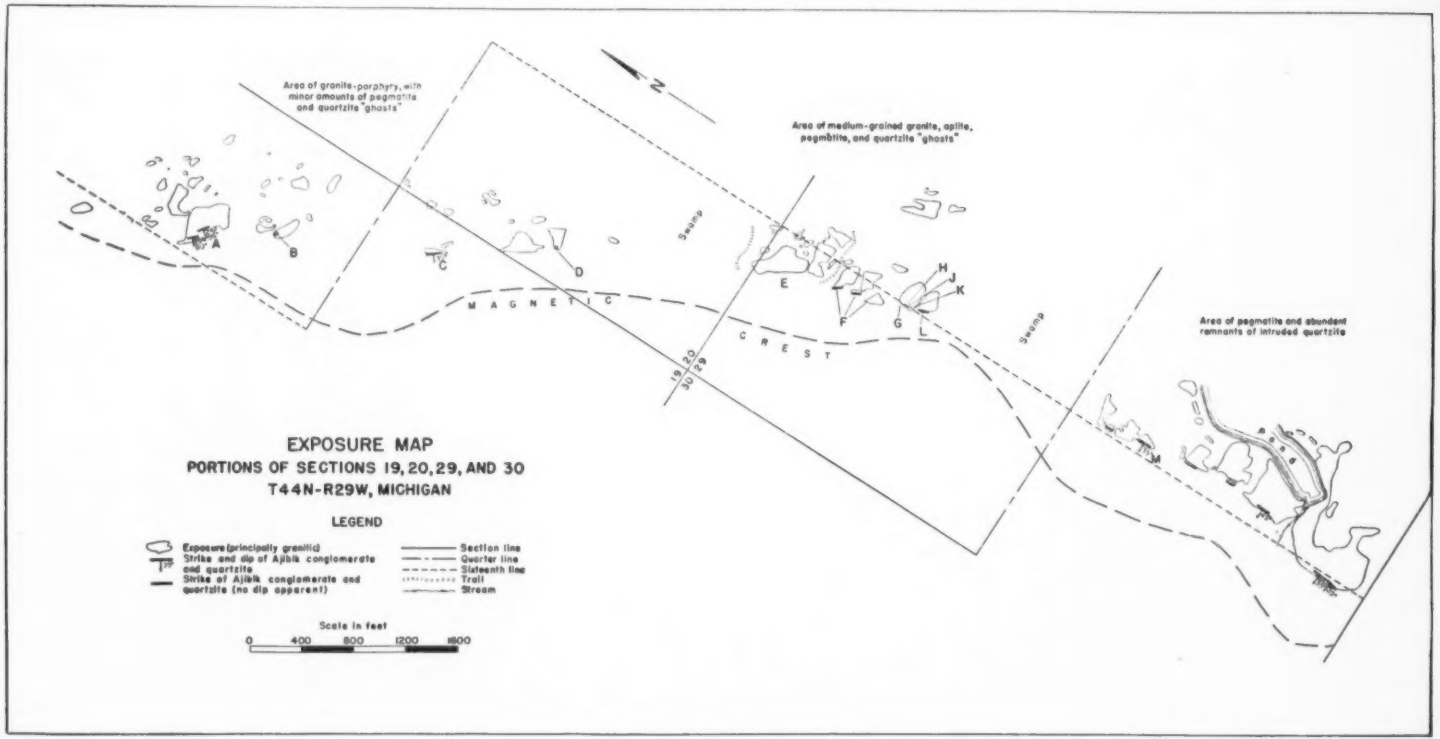

FIG. 2.—The Floodwood exposures

Subordinate feldspar-quartz pegmatite dikes and a few quartz veins intersect the granite-porphyry, with apparently a random orientation.

The granite-porphyry is prominently sheared, generally in an east-west direction, although the rock cannot in a broad sense be considered greatly deformed.

Stringers of rather remarkable regularity in outline and continuity, usually 2 inches or less in width and often 20 feet or more in length, are found in some abundance within the granite-porphyry. These strike from east-west to N. 70° E., and dip steeply to the north. They resemble quartz veins on weathered surfaces, but close examination shows them to be apparently fine-grained quartzite, containing biotite, some pyrite, and rounded quartz grains.

The exposure shown at *A* in Figure 2 is one of the most prominent in the area and is visible for considerable distances in all directions. Mantling portions of its steep west face, which is somewhat concave to the west, is rather thinly bedded quartzite, striking from N. 45° W. to N. 60° W., with an average dip of about 25° to the southwest. This dip is as steep as 80°, in places, apparently by reason of irregularities in the ancient erosional surface upon which the sediment was deposited. The sedimentary material consists in its lower portions of a finely conglomeratic horizon from approximately 6 inches to 1 foot in thickness; this is composed for the most part of clastic glassy quartz grains of perhaps $\frac{1}{8}$ inch in average diameter, in a matrix of quartz, sericite, chlorite, and biotite. A thin basal zone is locally feldspathic. This conglomerate passes upward into thin-bedded, vitreous, sericitized quartzite. The bedding of the conglomerate and quartzite is concordant with the surface of contact with the granite. A few stringers of quartzite extend into the granite for short distances, particularly near the northwest end of the exposure; these are interpreted as having developed from the sifting of sand into fissures on the old erosion surface. Similar crack-fillings are found at *B* and *D* in Figure 2.

At *C* sericitized quartzite identical with that at *A*, although perhaps not so markedly vitreous, occurs on the west slope of an elongate, low exposure of granite-porphyry. Here it strikes N. 50° W.

and dips 35° to the southwest, or about parallel to the granite face upon which it is found.

The intermediate area.—The granite of this portion of the Floodwood exposures is generally gray to pink to red in color, medium-grained, and biotitic, and is apparently merely a phase of the granite-porphyry to the north. It is, however, much more abundantly intruded by pegmatite dikes, and has numerous areas of pegmatite which grade by diminution of crystal sizes into the medium-grained material surrounding them. Likewise, aplite is present in subordinate quantities. Within the granite are found occasionally irregular shreds or wisps of biotitic, chloritic, quartzose material which are thought to represent "ghosts," or highly metamorphosed remnants of intruded quartzite.

On and near the base of the steep west face of the exposure at *E* are numerous fragments of conglomerate, consisting of well-rounded or ellipsoidal pebbles and cobbles of quartzite and vein quartz up to about 1 foot in maximum dimension, in a matrix of sericite, quartz, and biotite. Narrow crack-fillings of quartzite are observed to extend into the granite from this face.

At *F* conglomerate similar to that just described, but generally with smaller pebbles of quartzite and vein quartz, is found to be overlain by sericitized quartzite. Here the strike is from N. 30° W. to N. 40° W., with no dip apparent.

Resting on the granite at *H* is conglomerate about like that described as present at *A*, but with the matrix composed of biotite, chlorite, and, subordinately, quartz. The conglomerate seems to be overlain by a thin horizon of banded grünerite-magnetite-quartz rock at *J;* this material was apparently formed by thermal metamorphism of a ferrous iron-bearing sandstone, clastic quartz grains being apparent under the microscope. Above this is relatively coarse-grained, biotitic, sericitized quartzite at *K;* immediately overlying this and in conformable contact with it is highly ferruginous quartzite which is now so thoroughly decomposed as to be a true sandstone. These exposures, which are found within a small area on the west slope of the granite outcrop, are not continuous, but the stratigraphic positions mentioned seem to be correct. At *G*, near the

north end of the outcrop, are numerous fragments of partially decomposed ferruginous quartzite which are approximately intermediate between quartzite and sandstone in their state of aggregation. Some of these contain distinct laminae of hematite up to $\frac{1}{8}$ inch in thickness.

At *L* is conglomerate striking N. 20° W. Mention should be made that in Figure 2, as at *L*, the plan view of the location of the sediments is somewhat misleading. It would appear from the plan that conglomerate at *L* is stratigraphically above the quartzite-grünerite-magnetite rock, and conglomerate at *K*, *J*, and *H;* actually the two conglomerates are the same, but that at *L* is located at a point lower on the steep, west-facing slope, consequently farther west along the dip, than that at *H*.

The southern area.—The granite of the southern area is made up almost entirely of gray, medium-grained pegmatite containing orthoclase, microcline, quartz, acid plagioclase, and some biotite. Again there is no reason to believe that this rock represents anything but a phase of the granite-porphyry of the Southern Complex.

The granite contains numerous remnants of material readily recognizable as quartzite. These are obviously intruded by the granite and commonly occur as stringers up to 2 feet in thickness, trending approximately east-west. In composition they range from quartzite showing intense sericitization to schistose-sericite-quartz-biotite rock. Many possess a wavy, locally contorted aspect.

At the outcrop marked *M* in Figure 2 the mutual relations of granite, intruded quartzite, and conglomerate with its overlying quartzite are perhaps more clearly indicated than at any other point in the area of the Floodwood exposures. The conglomerate, consisting of numerous well-rounded pebbles and cobbles of vein quartz and quartzite in a sericitic, biotitic (locally amphibolitic), quartzitic matrix, and measuring about 1 foot or less in thickness, bevels with a north-south strike across the granite and its intruded stringers of of east-west trending quartzite. The contact between conglomerate and intruded quartzite is plainly visible in several places; it is a sharp and well-defined surface of separation, and there can be no question that a tremendous period of intrusion and erosion separates the two sediments. In one place the intruded quartzite swings about

and parallels the strike of the conglomerate; here it is thoroughly sheared, with the shearing parallel to the conglomerate contact in both strike and dip.

Two generations of quartz veins are here present. The older set strikes east-west, cuts the granite, and is beveled by the conglomerate. The younger strikes about N. 20° W. and transects both granite and conglomerate with its overlying quartzite.

The exposed thickness of conglomerate and quartzite unconformably overlying the granite is rarely more than 30 feet. The quartzite is thoroughly indurated, biotitic, and sericitized near its base, the degree of induration and intensity of sericitization decreasing upward and westward from the conglomerate. Locally the quartzite is highly amphibolitic and biotitic, and should be classed as a graywacke.

The Floodwood exposures demonstrate that granite-porphyry and its various phases have intruded a quartzite; that the igneous rock and invaded quartzite have been truncated by erosion; that a conglomerate-quartzite series has been deposited unconformably on the eroded surface; that emanations doubtless from a buried intrusion, apparently rising along the surface of unconformable contact for the most part, and preceding, accompanying, or following tilting of the sequence, have thermally metamorphosed the younger sedimentary series.

The granite-porphyry of the Floodwood exposures, which is identical with that of most of the Southern Complex, is here named the Ford River granite, because the west branch of the Ford River approximately parallels these exposures at distances of from $\frac{1}{8}$ to $\frac{3}{4}$ of a mile to the west.

CORRELATION OF SEDIMENTS OF THE FLOODWOOD EXPOSURES

It is the writer's belief that the quartzite which has obviously been intruded by granite-porphyry and its various phases is the Sturgeon, which is usually referred to the Lower Huronian. The Sturgeon quartzite is known to be present in the Sturgeon River tongue a short distance to the south of the Floodwood exposures; however, it, or its equivalent, has not been previously recognized around the western and northern margins of the Southern Complex

from the Sturgeon River tongue to the eastern part of the Marquette synclinorium. The thermally metamorphosed conglomerate which rests unconformably upon both the granitic rocks and the intruded quartzite is believed to be the Ajibik of what is customarily regarded as Middle Huronian; this is likewise true of the vitreous, sericitized quartzite, the grünerite-magnetite rock, and the decomposed ferruginous quartzite which overlie the conglomerate. If this correlation is correct, the granite-porphyry of the Southern Complex is post–Lower Huronian and pre–Middle Huronian in age.

It is realized that this correlation may be attacked. Those who advocate a post-Huronian age for the granite-porphyry will doubtless claim the conglomerate and overlying material to be basal Keweenawan or even younger. Proponents of a Laurentian age for the granite-porphyry will perhaps regard the intruded quartzite as Keewatin; such a view is considered hardly tenable, because quartzite, if present in the known pre-Huronian rocks of the Southern Complex, is assuredly far from abundant in these rocks. It cannot be denied, however, that this possibility exists.

In support of the correlation advanced, attention is called to the magnetic crest shown in Figure 2, located a short distance west of the line of exposures. The magnetic readings, fading westward from the crest, indicate a west-dipping magnetic horizon, which has always in the past been regarded as the Negaunee iron formation. This magnetic horizon seems to overlie the conglomerate-quartzite series flanking the granite outcrops on their west slopes. Although the iron formation is not exposed, the magnetic observations have been uniformly accepted as indicating continuity of the Negaunee iron formation along the west margin of the Southern Complex, from the Magnetic Mine near the Republic syncline on the north to the Turner tongue on the south. In fact, this continuous magnetic crest furnishes one of the chief bases for the correlation of the iron formation of the Sturgeon River, Felch, Calumet, and Menominee ranges with the Negaunee iron formation of the Marquette and Republic areas. One who would claim a post-Huronian age for the material which the writer regards as Ajibik must of necessity advocate the existence of a post-Huronian iron formation (not known to exist), assert that the magnetic observations have no significance

as to the presence of iron formation in the area, or consider that iron formation is present, but is overlain unconformably and with angular discordance by the Floodwood conglomerate and quartzite which are observed to rest unconformably upon the granite-porphyry. Of these hypotheses, the third is perhaps the most logical, and cannot be definitely disproved on the basis of the evidence now available in the Floodwood area proper. However, the presence of secondary grünerite and magnetite in the sedimentary sequence unconformably above the granite indicates the existence of ferrous iron as a primary constituent of these sediments—a condition perhaps not normally to be expected in otherwise well-oxidized material if this material has been derived from the weathering of a Huronian iron formation. It seems more likely that the ferrous iron indicates the inception of chemical sedimentation which would ultimately have given rise to iron formation. Further, no chert fragments were observed in the conglomerate or overlying quartzite.

In support of the correlation advanced by the writer, it is essential to consider an exposure of conglomerate at the southeast end of the Republic syncline which has been the cause of much debate in recent years. The Republic conglomerate and that in the Floodwood exposures seem to reveal the same sequence of events in the geologic history of the Southern Complex.

THE REPUBLIC CONGLOMERATE

The Republic conglomerate is located a short distance south of the town of Republic, Michigan, and the upper portions of the principal exposure, adjacent to the Republic baseball park, are visible from State Highway 95. The occurrence was first described by Smyth[5] in 1893, was referred to by the writer[6] in 1936, and has been dealt with in detail by Lamey in his most recent paper.[7] In a sketch accompanying his article Lamey indicates the location of most of the major features of the occurrence. So far as is known, no one

[5] H. L. Smyth, "A Contact between the Lower Huronian and the Underlying Granite in the Republic Trough, near Republic, Michigan," *Jour. Geol.*, Vol. I (1893), pp. 16–29.

[6] *Op. cit.*, p. 327.

[7] "Republic Granite or Basement Complex?" *op. cit.*, pp. 495–501.

familiar with the area regards the conglomerate here present as any other than basal Ajibik.

Both Smyth and the writer stated that the contact between the conglomerate and the underlying granitic material is erosional in nature. Lamey, however, believes the contact to be one of intrusion.

The writer, from field study, identified the material making up large boulders in the conglomerate as that of the granitic rock underlying the conglomerate, and stated that these boulders are composed of mashed granite-porphyry lying with their planes of foliation at angles to the strike of the foliation in the mashed granite-porphyry below the conglomerate.

Lamey, through extensive examination of thin sections, supplemented by field mapping, reached the conclusion that the larger boulders of the conglomerate are principally quartzite, and denied that these were derived from erosion of the underlying granite. His principal arguments in favor of intrusive relations between conglomerate and granite are thermal metamorphism of the conglomerate and the presence of small pegmatite intrusions and quartz veins cutting granite and conglomerate alike. He states that "if the granite in this vicinity is older than the Huronian formations, as postulated by Dickey, one is faced with the anomalous conditions of extensive contact metamorphism without any intrusion that produced it."[8]

If this statement were correct, the conditions would most assuredly be anomalous. As a matter of record, the writer recognizes fully the thermal metamorphism of this conglomerate and the associated Huronian rocks, but regards it as produced by emanations from a post-Huronian magma which is represented by the small pegmatite intrusions and quartz veins observed to cut the conglomerate and underlying granitic rock. That the contact between the conglomerate and the granitic material beneath it is other than fundamentally erosional is here denied.

The disagreement concerning the nature and source of the larger boulders of the conglomerate can be largely overcome by a demonstration that each of the hypotheses is in part correct. The boulder material is prominently quartzitic, and is in varying degree also

[8] *Ibid.*, p. 499.

mashed granite-porphyry. Contradictory as this may seem, it is clarified by the statement that a considerable portion of the granitic material in erosional contact with the conglomerate is quartzite which has been intruded and granitized by the granite-porphyry. This granitized sediment has yielded the boulders to the overlying Ajibik conglomerate, and in some of these boulders "ghosts" of sericitized feldspar phenocrysts can be seen. One of the large boulders is dominantly quartzite, but most of the others consist of mashed granite-porphyry and granitized quartzite.

The evidence indicates that a quartzite, believed to be a part of the Lower Huronian, has been invaded by the granite-porphyry. At the south end of the exposure, just south of the point marked *B*[9] on Lamey's sketch, is a tabular inclusion of biotitic quartzite in the granite, having a maximum thickness of about 6 inches, striking roughly normal to the overlying northeast-trending conglomerate, and dipping steeply to the north. The bedding in this inclusion is observed to be generally parallel to its contacts with the granite—a fact which in the writer's opinion eliminates the possibility of its being a filling of a crack in an old erosion surface.

Further, a short distance to the north of this inclusion is a band of quartz-sericite-biotite schist (thought to be sheared impure quartzite), about 3 feet wide, intruded by vein quartz. This is margined by granite, which apparently intrudes it. As in the instance mentioned above, the strike of this inclusion is approximately normal to that of the overlying conglomerate, although the contact between the two is not visible.

In addition, the granite-porphyry is highly quartzose (much of the quartz having a clastic appearance) and contains abundant sericite and biotite at and near its contact with the conglomerate. To the writer this indicates the presence of partially assimilated quartzite. The contact between conglomerate and granitized quartzite is sharp and well defined; in its general northeasterly trend it bevels the strike of foliation in the mashed granite-porphyry and granitized quartzite, and also that of the quartzite inclusions in the granite-porphyry.

The lithologic identity of most of the large boulders in the Ajibik

[9] *Ibid.*, p. 496.

conglomerate with the granitized quartzite underlying it, together with the discordance between the conglomerate strike and the trend of the foliation (and that of the quartzite inclusions) in the granitic material beneath the conglomerate, demonstrates erosional relationships between conglomerate and granite-porphyry. This conclusion seems valid despite thermal metamorphism of the conglomerate and its invasion by small amounts of pegmatite and quartz veins.

The granitized quartzite is not certainly Lower Huronian; nevertheless, it is apparently pre-Ajibik in age, and, as previously indicated, quartzite is by no means a common constituent of the pre-Huronian rocks in the Southern Complex or adjacent areas.

The Floodwood exposures and the Republic conglomerate occurrence give evidence of the same major events in their orogenic history. Both show that granite-porphyry has intruded quartzite; that the invading granite and invaded quartzite have been truncated by erosion; that conglomerate has been deposited on the eroded surface; and that this conglomerate and its associated rocks have been tilted or folded and thermally metamorphosed, probably in post-Huronian time, by emanations from an intrusion not exposed in the Floodwood area, except possibly as minor quartz veins, and present only as small amounts of pegmatite and quartz veins in the Republic exposures.

In view of their complex nature it is small wonder that the Republic conglomerate outcrops have been a puzzle during forty-four years of intermittent study. In the writer's opinion, the principal retardant to the realization of their significance has been a lack of knowledge of the existence of what seems to be post–Lower Huronian, pre–Middle Huronian granitic intrusion in the region.

SUMMARY AND CONCLUSIONS

In the Floodwood and Republic areas of Upper Michigan evidence exists that quartzite, regarded as Lower Huronian, has been intruded by granite-porphyry, the dominant igneous rock type of the Southern Complex. The granite-porphyry and intruded quartzite are unconformably overlain by what is believed to be basal conglomerate of the Middle Huronian Ajibik quartzite. The sequence

has been deformed and thermally metamorphosed, probably by the influence of post-Huronian intrusion.

The granite-porphyry, named the Ford River granite, is, according to the writer's interpretation, post–Lower Huronian and pre–Middle Huronian in age. It has been considered post-Huronian and called the Republic granite by Lamey;[10] the term "Republic granite" is not desirable, since known post-Huronian granite is exposed only in small quantities in the vicinity of Republic; however, because it is established in the literature it is retained as a designation for the post-Huronian granite found in some abundance about the margins of the Southern Complex.

It is possible that the Ford River granite, in view of its intrusion of recognized sediments and its erosional contacts with the Middle Huronian, corresponds to the Algoman granite of the north shore of Lake Superior; in northern Minnesota the Algoman granite intrudes the Knife Lake series and is overlain unconformably by the basal Middle Huronian rocks. If the Ford River granite and the Algoman granites are ultimately shown to be correlatives, a number of differences in pre-Cambrian correlations in the Lake Superior district and areas to the north may be reconciled. The recognized separation in the Upper Peninsula of Michigan of the Lower Huronian from the Middle Huronian by a major period of orogeny would doubtless require revision of some of the stratigraphic nomenclature now applied to pre-Cambrian sequences on the south shore of Lake Superior.

ACKNOWLEDGMENTS.—The writer is indebted to Mr. G. W. Allen for assistance during the field mapping of a number of outcrops by plane table and telescopic alidade. Dr. V. L. Ayres, of the Michigan College of Mining and Technology, has made several valuable suggestions with respect to the Republic conglomerate and the age of the Floodwood conglomerate; the views expressed in this paper do not, however, necessarily coincide with his. A number of helpful criticisms have been offered by Mr. R. W. Marsden and Dr. S. A. Tyler, of the University of Wisconsin.

[10] "The Intrusive Relations of the Republic Granite," *op. cit.*, pp. 498–99.

REVIEWS

Stratigraphie und Tektonik der Pragser Dolomiten in Südtirol. By JULIUS PIA. Vienna: Published by the author, 1937. Pp. xvi+248; figs. 17; pls. 14 (including a geological map). $1.co.

This book is primarily a very detailed description of part of the dolomites of southern Tyrol, famous among geologists as the type region for the division of the Triassic system. Attention of American geologists may, however, be drawn to the fact that it has also some bearing on subjects of a more general interest. As stated in the Preface, the stratigraphic chapters are intended to be an exemplification of the author's theory of geological classification and correlation. This theory is based upon a thorough discrimination between purely chronological stages and rock members implying certain lithological characters.

In the description of the mid-Triassic Schlern dolomite there is contained a full account of what the author considers to be one of the most clearly exposed fossil coral reefs.

The tectonic part of the book deals especially with the interference of two thrust movements acting from north to south and from east to west, respectively. In describing these phenomena the author uses and expands the statistical methods set forth in previous papers (abstract in the *Journal of Geology*, Vol. XXXI [1923], pp. 527–28). They convey a clearer insight into the effects of faults upon the general strike of the strata, into the compensation of the thrust movement of rigid strata by close folding in soft ones, into horizontal torsions of certain blocks during their western movement, etc.

F. X. SCHAFFER

ERRATUM

Edward C. Cabot, "Fault Border of the Sangre de Cristo Mountains North of Santa Fe, New Mexico," in the *Journal of Geology*, Vol. XLVI, No. 1, p. 92. In the legend of the geologic map, *read* Picuris Tuff *for* Badito Tuff.

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IN HONOR OF

PROFESSOR ALBERT JOHANNSEN

With the academic year of 1937, Professor Albert Johannsen completed his long and distinguished services as an active member of the University of Chicago faculty and retired from teaching, as professor emeritus. With the relinquishing of teaching he has also retired from active editorship of the *Journal of Geology*, after having carried responsibility for the field of petrology ably for nearly thirty years. Many of his former students have wished to see their admiration and affection expressed in some tangible way. His colleagues and co-workers likewise have sought a means of acknowledging the debt which they and their science owe to Professor Johannsen, and of doing so while he is still a productive scholar with powers undiminished. The *Journal of Geology* also feels its heavy obligations.

To these many friends and admirers it has seemed fitting that we assemble, in *Festschrift* fashion, a group of notable contributions by men prominent in the general field to which Professor Johannsen has devoted himself, and that we publish these as a special supplementary number of the *Journal of Geology* dedicated to him. The participating authors, who have given so freely of their time, have contributed most in the preparation of this tribute; but with them in spirit are many others who remain unnamed.

THE EDITORS

THE PROBLEMS OF THE RAPAKIVI GRANITES

HELGE G. BACKLUND
Upsala, Sweden

ABSTRACT

The rapakivi granites of Fennoscandia, characterized by Johannsen as "abnormal," include coarse-grained rocks having a peculiar ovoidal texture, controlled by the form of their potassium feldspars, which formerly served to define the whole group. When, however, it was realized that associated with the ovoidal varieties there are related granites having equigranular and porphyritic textures, notwithstanding some textural abnormalities, stress was laid on their age relations, and all the granites of inter-Jotnian age in Fennoscandia were grouped together. In the field these granites are vicarious with the Jotnian sandstones and have a similar distribution on or near the boundaries between the Svecofennian and Gothokarelian orogenic areas. The Jotnian quartzites were long ago designated as "Oldest Red" (Sederholm), i.e., as constituting the youngest continental sediments of pre-Cambrian age and representing the Molasse facies corresponding to the denudation of the Gothokarelian folds; consequently the rapakivi rocks are to be regarded as Molasse granites. A systematic discussion and reciprocal confrontation of sixteen well-known characteristics of these granites and their field appearances lead to the conclusion that they must have been formed at the expense of the Jotnian sediments and its closest Archean neighbor-rocks by a process akin to metasomatism. All other hypotheses lead to hopeless contradiction. The transformation process depends upon the influx of alkali aluminates as "emanations," in quantities corresponding to and fixed by the original porosity—actual and potential—of the parental sandstone; a surplus of "emanations," with consequent increment of volume, giving birth to true dynamic magmatic rocks represented by acid surface volcanics of rheomorphic origin. Possible mechanisms of influx are discussed and also the conditions favoring bedwise "granitization" leading to the formation of sheetlike bodies of granite differing somewhat one from another in age, composition, field position, and erosional peculiarities. The "abnormality" referred to by Johannsen is thus related to an equivoluminal "metasomatic" transformation of Molasse sandstone sequences, by influx of particular elements. In this respect the rapakivis are quite different from other granites hitherto described as being of similar provenance; nevertheless, they are accompanied by magmatic rock-types of rheomorphic origin, the formation of which involved increase of volume, as described by the writer and several other authors elsewhere.

INTRODUCTION

Just as the anorthosites raise many specific problems generally treated only as a special problem of differentiation, so, although perhaps less widely recognized, there exist many stimulating problems connected with the rapakivi granites of Fennoscandia. These problems have never before been discussed as a whole, although they all show a marked interdependence. They may be classed under the following headings: (1) morphology, (2) structure, (3) regional considerations, (4) association, (5) weathering, (6) tectonics, (7) stratigraphy, (8) texture, (9) mineralogy, (10) crystallization, (11) chemistry, (12) differentiation, (13) form of rock body, (14) emplacement,

(15) genetics, and (16) radioactivity. Nearly all these items about the rapakivi granites have been treated elsewhere independently and have led to puzzling and contradictory results, although the most eminent petrologists even lately have devoted thorough special researches, both in the field and in the laboratory, to these interesting rocks.

The rapakivi granites have always been considered as a special problem of Finland. Sederholm, whose earliest geological work[1] introduced the rapakivi granites into broader petrological thought and whose last publication, after his exceptionally successful researches on the geology of Fennoscandia, returned to these rocks,[2] always pointed out their regional significance for the whole of Fennoscandia. As such they were discussed by Holmquist,[3] together with other granitic rocks of Sweden, with special reference to their chemical and textural evolution. But Sederholm[4] over and over again laid special stress on the *geological* position of the rapakivis, rejecting all attempts to group them with granites of rapakivi resemblance yet of a different *geological* position within Fennoscandia. So he has excluded therefore all granites of the Filipstad group of south-central Sweden, those of southeastern Sweden (Götemar and Jungfru granites), the last one with some hesitation, from the rapakivi clan, in spite of their chemical and partly even textural likeness, in this case often arguing against the Swedish geologists. These excluded granites are of a late Flysch age ("late orogenic," "late synkinematic") pertaining to the folded area of the Gothokarelides,[5] while the true rapakivi granites are of a late Molasse age ("late

[1] J. J. Sederholm, Über die finnländischen Rapakiwigesteine," *Tschermaks Min. u. Petr. Mitt.*, Vol. XII (1891), p. 1; "Sind die Rapakiwimassive als Lakkolithe oder Massenergüsse zu deuten?" *Mitt. naturwissensch. Ver. f. Neu-Vorpommern u. Rügen*, Vol. XXIV (1892).

[2] "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," Part III: "The Åland Islands," *Bull. comm. géol. Finlande*, No. 107 (1934).

[3] P. J. Holmquist, "Studien über die Granite von Schweden," *Geol. Inst. Upsala Bull.* 7 (1906), pp. 77–269.

[4] "On the Geology of Fennoscandia, with Special Reference to the Pre-Cambrian," *Bull. comm. géol. Finlande*, No. 98 (1932).

[5] H. G. Backlund, "Die Umgrenzung der Svekofenniden," *Geol. Inst. Upsala Bull. 27* (1937), pp. 219–69.

post-orogenic," "later post-kinematic") of the same area, and consequently occupy a quite different position within the structures of Fennoscandia, although their genesis may have something in common. He made distinction between the granites of the third group (Obbnäs-Onas granites in Finland, Rätan granites in Sweden) as being of an early Molasse age ("early post-tectonic," "early post-kinematic") and those of the fourth group, to which belong the rapakivi granites; both groups are, as we now know, linked to the Gothokarelian orogeny.

Sederholm, as chief geological proponent of the rapakivi granites, has made distinction within this group between true (ovoidal) rapakivis and rapakivi granites in narrower sense, on the one side, and their superficial equivalents, on the other. He found the two former varieties mostly associated and emphasized the nearly common age of all the three types, a statement fully confirmed by later investigators.[6] Sobral,[7] and recently von Eckermann,[8] picked up this suggestion and definitely, by extensive field and laboratory investigations, extended the special rapakivi problem of Finland into a common Fennoscandian one. The last-named, in his valuable memoir on the Loos-Hamra region, was able to give some idea of the magnitude of interval between the emplacement of the different members of the rapakivi group, thus pointing to the great role which this rock clan played in the geological evolution of Fennoscandia, and hence filling in the great gap between the end of the Gothokarelian (Algoman) revolution and the late pre-Cambrian. This record embraces the order of events accompanying the formation of the great Eparchean peneplain, in which the rapakivi group of rocks was involved, i.e., it corresponds to the time interval between 750 and 550 million years ago (approximately), for which the details hitherto known from Fennoscandia were very scanty.

[6] W. Wahl, "Die Gesteine des Wiborger Rapakiwigebietes," *Fennia*, Vol. XLV, No. 20 (1925); V. Hackman, "Das Rapakivigebiet der Gegend von Lappeenranta (Willmanstrand)," *Bull. comm. géol. Finlande*, No. 106 (1934); P. Eskola, "On Rapakivi Rocks from the Bottom of the Gulf of Bothnia," *Fennia*, Vol. L, No. 27 (1928).

[7] J. M. Sobral, *Contributions to the Geology of the Nordingrå Region* (Uppsala, 1913).

[8] H. von Eckermann, "The Loos-Hamra Region," *Geol. För. Stockh. Förh.*, Vol. LVIII (1936), pp. 129–343.

The writer has never published any report on the rapakivi rocks; he has no intention of recapitulating any of the valuable investigations upon them, the list of publications of which is to be found in the exhaustive memoirs of Wahl[9] and of Hackman.[10] Yet as he knows from field excursions all the chief areas of the true rapakivis within Finland and Sweden (and Norway), and as he has always been puzzled by the remarkable field appearance of these rocks and by the problems they have raised, he wishes to confront, on the basis of field experiences together with the aid of evidence obtainable from the literature, the questions which these rocks present and to determine whether there are some general conclusions to be drawn from the facts observed which will contribute to an adequate solution of the problems which fall under the headings listed above.

The rapakivi rocks now under consideration are those of the Salmi area, east of Lake Ladoga; the Viborg area with the island of Hogland in southeastern Finland (by far the largest area); the Nystad area, comprising the minor areas of Laitila and Vehmaa in southwestern Finland; the Åland area which closes the Bottnian Gulf to the south; and the Dalarne area with westernmost Helsingland in central Sweden. The rapakivis of Norway, southwest of Trondhjem,[11] are not considered because their position is somewhat doubtful, since they were deformed in the Caledonian orogeny. This is also the case for the Olden area. The areas of Nordingrå[12] and Ragunda[13] are not especially brought into the discussion either, although their characters conform well with those of the forementioned areas, because their further revision is to be expected in the near future.[14] All these areas have been described more or less in detail, even rock analyses being available, except for the eastern Salmi area, which still awaits closer investigation. The writer has studied in the laboratory slides and samples of most of the rocks concerned.

[9] *Op. cit.* [10] *Op. cit.*

[11] C. W. Carstens, "Rapakiwigesteine a. d. westlichen Grenze des Trondhjemgebiets," *Norsk Geol. Tidskr.*, Vol. VIII (1924–25), pp. 81–92.

[12] Sobral, *op. cit.*

[13] A. G. Högbom, "The Igneous Rocks of Ragunda, Alnö, Rödö and Nordingrå," *Geol. För. Stockh. Förh.*, Vol. XXXI (1909), p. 347.

[14] The work of Sobral and von Eckermann is expected to result in more detailed knowledge of these areas.

THE PROBLEMS

MORPHOLOGY

The rapakivi areas form undulating plains in which the undulations have a slightly larger amplitude than those of the surrounding Archean areas of mixed rocks. They fit very well into the so-called sub-Jotnian peneplain, whose insignificant local slopes they share. But there is a marked yet not extremely high step between the rapakivi flat and the surrounding peneplain, and this difference in height increases conspicuously to the west. In consequence of this, the rapakivis were originally believed to lie above the Eparchean peneplain, the conformity of their upper surface with the surrounding peneplain and with their supposed floor being explained by their form being that of extrusive sheets. When it was realized that the textural features of the rapakivi sheets are inconsistent with their being lava flows and the Upper Jotnian was found to rest with erosional unconformity above the rapakivis, the latter were put below the sub-Jotnian peneplain. This peneplain was to be compared with the Eparchean one.[15] Quite recently von Eckermann[16] was able to demonstrate that the so-called sub-Jotnian peneplain, above the rapakivis, is an erosional surface of minor importance and that the great post-Archean unconformity (the Eparchean peneplain) runs below the rapakivis, the latter developing as sheetlike intrusions within the lower Jotnian. The base of the rapakivis should have been marked by the peneplain, while their flat tops should have been delineated by the immediately succeeding sandstone beds and an inter-Jotnian peneplain. It is observable that the sheetlike morphological appearance of the rapakivis has something to do with the footwall peneplain and with the flat roofing sediments in the west, yet it remains unexplained why an acid intrusion of conspicuous viscosity does not bulk out beneath the comparatively thin cover of sediment.

STRUCTURE

The rapakivi granites are characterized by broad, regular, and well-spaced jointing. There are, in general, two sets of vertical joints

[15] A. C. Lawson, "The Eparchean Peneplain," *Bull. Geol. Soc. Amer.*, Vol. XLV (1934), pp. 1059–72.

[16] "The Jotnian Formation and the Sub-Jotnian Unconformity," *Geol. För. Stockh. Förh.*, Vol. LIX (1937), pp. 19–59.

nearly at right angles to each other, one of which is dominant and more easily traceable. The jointing is independent of the outer boundaries of the areas and conforms neither to the jointing nor to the schistosity of the surrounding country rocks. In some parts of the area one set of joints seems to be the dominant one, in others the second direction, or a slightly different one, is more prominent. In places small movements along one set of joints are to be noted, yet a general plan or rule of tension cannot be established for the areas. The third horizontal set of joints forms the best parting of the rapakivi and aids in quarrying. This parting dips outward at low angles in the outskirts of the areas, yet abruptly, about some 100 meters from the outer margin, resumes a nearly horizontal position, with slight undulations, the general slopes of which follow the subdued landforms of the surrounding peneplain. Even the horizontal joints are well spaced so that they, together with the vertical joints, predispose the rocks for profitable quarrying. The greatest monoliths known in the history of the Fennoscandian stone industry were quarried from the rapakivi granites. The erratic glacial boulders of rapakivi in the periphery of the ancient Fennoscandian land-ice, if not destroyed by weathering, rank among the biggest ones, and the glacial drift on the leeward side of the special rapakivi areas is sometimes rather blocky. The quarrying industry after having temporarily abandoned the rapakivis in consequence of local or regional defects has over and over again returned to them as the most profitable ones. The jointing is independent of the outer and inner contacts.

There are no evidences of crushing or other traces of regional deformation within the rapakivi areas, either mega- or microscopic; the absence of such signs has made it certain that the rapakivis are entirely post-orogenic–post-kinematic within the geologic structures of Fennoscandia.

If the jointing be a representation of the cooling history of an igneous body, its spacing and regularity in this case should indicate a very deep-seated origin with a slow and gradual fall of temperature; the horizontal jointing, however, remains unexplained as also its independence of contacts and surroundings. The facts stated in

the foregoing section are at variance with this deduction of deep-seated origin. Some other explanation is needed.

REGIONAL CONSIDERATIONS

The granite areas under discussion show a very remarkable distribution (Fig. 1). They are roughly grouped along an east-west line, which nearly coincides with the supposed boundary line between the Svecofennides, with an approximately east-west trend, and the Gothokarelides, with a north-south to north-northwest strike. The two easterly ones, the Salmi and the Viborg areas, are situated on either side of the deep north-south Ladoga depression, the age of which is unknown except in so far as it seems to harbor some late Gothokarelian (post-orogenic) Jotnian sandstones. The visible parts of the remaining areas, and the small poorly exposed Gevle area, are grouped around the southern end of the Bottnian depression, which is older than the rapakivi granites. Only the Hamra area, with the adjoining western Dalarne area of corresponding volcanics, is a little removed from this depression. A real dependence on these depressions cannot therefore be demonstrated. A second group of rapakivi granites, that of the Nordingrå-Ragunda areas, is arranged along a northerly east-west line, the granites again being located within areas of older rocks, the strikes of which vary from east-west to south-southeast–north-northwest.

Neither the outlines of the granite areas, nor their other major or minor geological features, show any but casual conformity with or dependence on the older pre-existing structures. Their boundaries pass transgressively across the various formations of the older complexes with no traces of mutual interference. The older structures show not the slightest deviation or special crowding as they approach the boundary lines. There are no east-west or north-south faults demarking the morphological or geological trends referred to above from which any boundary relationships can be inferred. There are no faults younger than the rapakivi granites, and of fairly circular course, to separate the rounded rapakivi areas from the surrounding rock complexes. The granites behave just as if they were enormous, deep-seated, and discordant intrusive bodies of batholithic habit, a deduction which agrees with the conclusion reached in

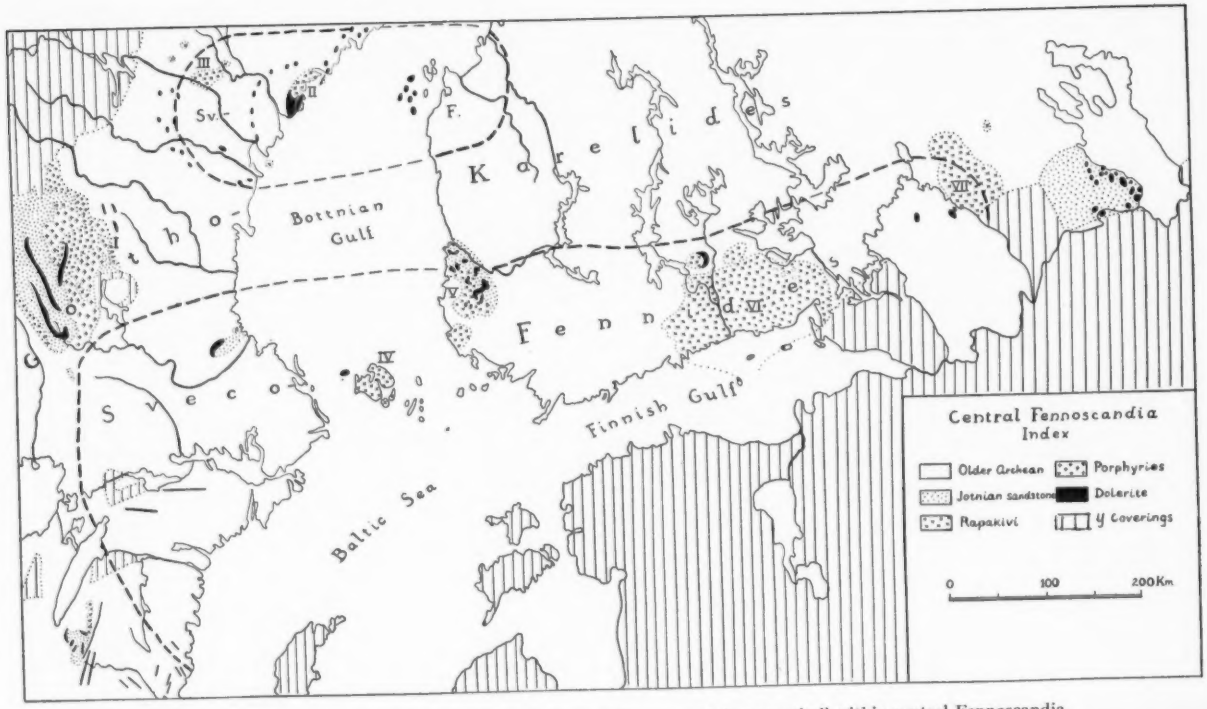


FIG. 1.—Distribution of late Gothokarelian Molasse sediments and "magmatics" within central Fennoscandia

the preceding section. Yet the exo-contact action is too insignificant and the alteration of the sparse and peripheral exogene inclusions of country rocks is too slight for such an interpretation. Furthermore, dynamic traces of such a batholithic intrusion are completely lacking.

ASSOCIATION

There are four topics of association to be considered in this connection, all of very great importance for the understanding of these rocks and their role within Fennoscandia. They are: the association (*a*) of rapakivi granites with post-orogenic Gothokarelian ("post-Archean," yet "pre-Cambrian") sediments, (*b*) of rapakivi granites with their own surface flows, (*c*) of different deep-seated members of the rapakivi within the same area, and (*d*) of rapakivi granites with basaltic rocks (an association suggestive to some of "contrasted differentiation").

a) ***Association of rapakivi granites with post-orogenic Gothokarelian sediments.***—It has become a rule in Fennoscandia, when encountering a Jotnian sandstone area, to search for rapakivis or their effusive equivalents in the neighborhood. All the granite areas, except those of Åland and Viborg, are bordered by or appear within Jotnian sandstone areas. Even for these exceptions the rule holds good because lately within the Viborg area, which is heavily covered by glacial drift, erratic but local boulders of post-Archean yet pre-Cambrian type have been found;[17] while the numerous boulders of Jotnian sandstone within the Åland area indicate the close proximity of the Jotnian sandstone on the sea floor to the north. The close geological relationship between rapakivi granites and sandstones was at first denied by Swedish geologists because of the long erosion interval that would be necessary (on the old conception of their very deep-seated position within the crust) for uncovering the granites by erosion to form the sedimentary Jotnian; consequently in Sweden the Dala porphyries, and related rocks in other parts of Sweden, were separated from the rapakivi group because of those postulated long-erosion intervals. Uniformity of viewpoint was re-

[17] C. E. Wegmann, "Sur un nouveau conglomérat précambrien de Taipalsaari," *Bull. comm. géol. Finlande*, No. 92 (1930), pp. 15–17.

FIG. 1.—Distribution of late Gothokarelian Molasse sediments and migmatites within central Fennoscandia

stored by three field investigations. First, Sobral,[18] in the Nordingrå area, stated that there is an arkose sandstone older than the ordinary Jotnian sandstone, separated from the latter by erosional and angular unconformities, but still younger than certain rapakivis and their associates of which they represent the erosional detritus. Then Sederholm[19] stated that there exists a quartzitic sandstone formation older than the rapakivis, but still younger than the latest pre-Cambrian orogenic movements and separated from the rapakivis and still more from the true Jotnian by a long erosional interval; this formation was named Hoglandian, as its vestiges were recognized on the island of Hogland. Recently von Eckermann[20] traced this formation beneath the Jotnian, from which it is separated by unconformities so that it is of early post-orogenic position. Yet it contains volcanics and plutonics of its own, the latter representing the granites of Sederholm's third group. By misunderstanding his own quotations from Sederholm, von Eckermann covered this lower post-orogenic sedimentation complex with a new name—the Noppi formation. The Jotnian of older conceptions above the Noppi-Hoglandian was shown to consist of at least three or four divisions, each separated from the other by erosional intervals or sedimentation gaps. Each division, except the uppermost, contains acid volcanics and plutonics of the rapakivi group. The uppermost one (the "Oldest Red") corresponds to the Jotnian in a narrower sense. Each later division consists to a great extent of detrital fragments of the earlier one, including pebbles of its "magmatics," i.e., the rapakivi granites. It follows that the rapakivi granite of each division was uncovered before the later one was deposited; and the later one was fully cemented before the emplacement of its own acid magmatics. The cover upon the granites cannot have been of any considerable thickness because, if it had been, very great vertical movements would have to be postulated for erosion purposes and for the succeeding redeposition. Yet vertical movements of some amplitude may have occurred, alternating upward and downward, just

[18] *Op. cit.*

[19] "On the Geology of Fennoscandia, with Special Reference to the Pre-Cambrian," *op. cit.*

[20] "The Loos-Hamra Region," *op. cit.*

as is characteristic of areas of a Molasse sedimentation. The rapakivis and their enclosing sediments are bound together as representing a Molasse with its typical rhythm of sedimentation reflecting its characteristic movements. The observations referred to may be valid for all rapakivi areas, but erosion has reduced the visible traces of their similar genetic evolution schematically sketched above. Both the repeated erosional uncovering within Jotnian times and the close association of granites and sandstones which still exists point to some reciprocal relationship; at all events these phenomena indicate that the granites solidified at no great depth (p. 350).

b) Association of rapakivi granites with their own surface flows.— The rapakivis are one of the few pre-Cambrian ("magmatic") suites from which with certainty both volcanic and plutonic equivalents are known. The volcanics, even true superficial flows, if present always appear in the immediate neighborhood of the plutonics. Yet the volcanics do not appear in connection with each of the aforementioned areas. In some areas they are represented by small dikes at a high level within the corresponding plutonics, i.e., they are considerably younger (Nordingrå, Åland). It can be concluded from the distribution of these hypabyssal types that the rapakivi volcanics once had a wider distribution in most parts of the rapakivi areas and that they have been considerably reduced by later erosion, as can be seen in the Ragunda and Nordingrå areas. The relations between the Hogland rapakivi volcanics and its Viborg mother-area are obscured by the sea. But in the eastern part of the Dalarne area (Hamra region) the close relationship between volcanics and plutonics can be easily traced, the former having a considerably wider distribution than the latter, especially in the west. There are at least two periods of extrusions in the Dalarne area, separated from each other by large erosional intervals, each set of extrusions being associated with, and covered by, sandstones. The plutonics that occur within each of these lower sedimentation sections are either somewhat later in their emplacement and somewhat deeper in position than the corresponding volcanics or are the only exposed representatives of the magmatics. In every case (1) the close association between the plutonics and the rapakivi volcanics

confined to fixed horizons of the sediments, (2) the early erosion of the latter, and (3) the rapid uncovering of the plutonics together with the continued erosion of the volcanics, all demand a very high level of position for the plutonics. On the other hand, all these facts, together with the additional fact that there are well-developed conglomerates in each series, demand a very complete cementation of each preceding section before the next came into existence. A stratigraphic correlation over wide and disconnected areas of the Jotnian sediments on the basis of their content of rapakivi extrusions becomes impossible, except perhaps for the uppermost layers, because of the great similarity between all the extrusions and the fact that they appear at different levels. A preliminary but convincing stratigraphic sequence of sediments, of extrusions, and of plutonics is for the first time established in the Hamra region (eastern Dalarne area),[21] after having been previously suggested in the Nordingrå area.[22]

c) Association of different deep-seated members of the rapakivi within the same area.—It has been known for a long time that within nearly every rapakivi area there occur several different textural varieties of deep-seated rocks, the varieties differing but slightly from one another in chemical and mineralogical composition. These textural aberrants have never been discussed in detail with regard to either their sequence or their conditions of congealing, being classed simply as "magmatic afterbirths" or marginal variants of the plutonic action. A closer examination has shown that the contact conditions between these textural modifications indicate a longer interval between their periods of emplacement than has been claimed in ordinary cases of "magmatic afterbirth." Moreover, it was implicitly accepted in the case of associated textural varieties that the coarse-grained ("ovoidal," "viborgitic," and "pyterlitic")[23] varieties were the earliest in their emplacement, i.e., the oldest members of the series, until Hackman[24] showed that there is no such regularity. It may be stated that in the Viborg area southwest of Vilmanstrand the contact between an even- and medium-grained (Lappee) rapakivi granite and an ovoidal ("pyterlitic") one is relatively sharp and of the same order as the contacts between the ovoidal ("viborgitic")

[21] *Ibid.* [22] Sobral, *op. cit.* [23] Wahl, *op. cit.* [24] Hackman, *op. cit.*

rapakivi and its Archean wall rock (pelitic metamorphics) at the southwestern boundary of the Viborg area, southeast of Borgå (Buckholm); the ovoidal rapakivi, without essentially changing its coarseness at the contact, spreads scattered ovoids ("unmantled") into the wall rocks, the number of ovoids rapidly diminishing outward. Consequently, the even-grained Lappee granite of the Viborg area is older than the coarse-grained ovoidal ("viborgitic" and "pyterlitic") granite, and no general sequence of rocks on textural grounds can be established, since in the Åland area the ovoidal granite seems to be the oldest one. On the one hand, it has been claimed that there are no sharp contact lines between the different textural varieties, whereas, on the other hand, it has more than once been emphasized that no transitions exist between the principal varieties. However, a closer examination[25] revealed the existence of relatively sharp contacts. In the Åland area Sederholm mentions both sharp and diffuse contacts; the present writer can in most cases, in the field, confirm sharp contacts, where uncovered. When it is considered that the varieties show only slight chemical differences, it is apparent that the internal contact action can develop no peculiar contact phenomena, even if the age difference between the rocks is of a conspicuous magnitude, because the original crystallization temperature of the different rocks is of the same order under equal geological conditions. If there exist textural differences between the two varieties, the temperature conditions and/or the geological conditions must have been different for the two intrusions; either the earlier intrusion must have cooled down before the second was emplaced or the roof conditions must have changed, or both. All this requires a certain lapse of time between the two emplacements. There still remains the space question for the later varieties; they all occupy large rounded or irregular areas within the earlier granites and show no signs of stoping, of assimilation, or of brecciation. Moreover, the possibility of simple assimilation of pre-existing granites gradually vanishes with the progressive evolution because texturally the successively later rapakivi rocks mostly testify to a gradual drop in the temperatures of solidification.

[25] I. Kanerva, "Über das Rapakivigebiet von Vehmaa im Südwestlichen Finnland," *Fennia*, Vol. XL, No. 40 (1928); Hackman, *op. cit.*

Again, von Eckermann,[26] from field examinations in the Dalarne area (Hamra), has found the solution, after Sobral[27] had taken the first steps toward it in the Nordingrå area, and after it had been sought for in vain in the original areas of Finland. After having noted the close connection between the volcanics and plutonics, the latter being rather of a hypabyssal position (i.e., of comparatively low temperatures of consolidation), von Eckermann realized that the granites intrude between or replace the Jotnian sandstones in such a way that they assume conformable sheetlike forms. The granites are thus separated by thicker or thinner layers of sediments and associated volcanics, the volcanics being superimposed on, or intercalated with, or partly replacing, the sediments. The granites are not contemporaneous because erosion pebbles of them are found in the roofing sediments, from which they are thus separated by an erosional unconformity. This unconformity means an uncovering of the granite sheet before the next section of sandstone sediments was deposited on top of it or in its neighborhood. In its turn this sedimentary section was invaded or replaced by a granite sheet, etc. There result a number of granite sheets figuratively piled on top of one another and separated by erosional unconformities and sandstone or conglomerate intercalations, the top sheet being the youngest. If now the intercalations become gradually thinner, the granite sheets rest immediately one on the other. As the erosional surface on top of each granite is by no means a level one, local faulting and subsidences having contributed to irregular rejuvenation of the erosion (see the maps of von Eckermann),[28] the boundaries of the superimposed sandstone areas in horizontal projection (on the map) become irregular, overlapping and sweeping out over the older floor rock. The boundary of the younger superimposed and replacing granite, too, becomes irregular, rounded, and curved; yet it is somewhat modified compared with that of the sandstone it replaces and intrudes. The processes of alternating sedimentation, erosion, uncovering, and local faulting, however, are those of typical Molasse areas. A case in which sheetlike partial or total superposition or overlapping of rapakivi granites of different structures and age oc-

[26] "The Loos-Hamra Region," *op. cit.* [27] *Op. cit.*

[28] "The Jotnian Formation and the Sub-Jotnian Unconformity," *op. cit.*

curs without sedimentary intercalations is represented by the rapakivi areas of Finland, those of the Swedish Nordingrå and Ragunda areas being transitional in this respect to the Hamra-Dalarne area.

In Table 1, on the basis of studies of maps and descriptions, and to some extent of field work, the different varieties of granites within each area are tabulated in order of decreasing age; no warrant is given for absolute correctness of order or for the possibility of stratigraphic correlation through the vertical columns.

The table shows that there is no possibility of stratigraphic correlation of the granites by means of texture, nor can the sandstone horizons of distant areas be correlated with any certainty according to the presence or absence of "magmatics." It shows also that the granites are sheetlike and of no particular depth of solidification and that they have shown no perceptible tendency toward differentiation during their long evolution, even if they be supposed to have ascended from a common magma chamber.

d) *Association of rapakivi granites with basaltic rocks.*—Since Törnebohm's classic investigations, the dike rocks of basaltic composition (diabases), which cut all the old pre-Cambrian structures of Fennoscandia in certain areas, have repeatedly attracted the interest of field geologists and petrologists. One was convinced that it was possible to classify these pre-Cambrian basic hypabyssal and volcanic rocks by means of their structural and mineralogical peculiarities, until Ljungner[29] showed that these are characteristic of their milieu, depth, and form of emplacement, and by no means of their age. On geological evidence they were classified as pre-Jotnian (in Sweden often sub-Jotnian) and post-Jotnian. Sederholm was the first to claim their close connection with Jotnian sediments, or with areas of Jotnian tectonics and rapakivi granites, although he showed that similarity of trend is not valid evidence of common age over all the areas under consideration, as was later supposed. The early and convincing observations of Sobral in the Nordingrå area, that there are at least three basaltic intrusions outcropping at about the same stratigraphical level which have an approximately similar trend al-

[29] E. Ljungner, "Die Morphologie der schwedischen Skagerrak-Küste," *Geol. Inst. Upsala Bull.* 21 (1937), p. 101.

though they differ in age and relative depth of solidification, had to be repeated by Krokström[30] on the great east-west dikes of central

TABLE 1

ORDER OF EMPLACEMENT OF THE RAPAKIVI GRANITES OF THE DALARNE-HAMRA, NORDINGRÅ, RAGUNDA, ÅLAND, NYSTAD, VIBORG, AND SALMI AREAS

Region	Intrusives			
	1	2	3	4
I. Dalarne-Hamra (von Eckermann)	?	Loberg (even grained)	Oreån (even grained)	Sandsjö (even grained)
II. Nordingrå (Sobral)	Ramsta (not homogeneous)	Ulfö (even grained)	Trysunda (beginning granitization of arkose)	Rödö? (quartz-porphyry)
III. Ragunda (A. G. Högbom)	Böle (syenitic, even grained)	Ragunda (even grained)	Quartz-porphyry	.....
IV. Åland (Sederholm)	Haraldsby (ovoidal, "mantled")	Haga (even grained)	Emkarby (quartz-porphyry)	Eckerö? (quartz-porphyry)
V. Nystad	Laitila (Laitakari,* Eskola)	Tarkki? (even grained)	Eurajoki (ovoidal, unmantled)	Väkkärä (even grained)	=Liesjärvi? (even grained, aplitic)
	Vehmaa (Kanerva	Tjusgrund? (even grained)	Kupusjärvi (ovoidal, unmantled)	Uhlu (even grained)	Riittiö?
VI. Viborg (Wahl, Hackman)	Lappee (tirilite *partim*, even grained)	Viborgite (ovoidal, "mantled")	Sinkko (porphyritic) Pyterlite? (ovoidal, "unmantled")	Kanalampi-Tysterniemi (quartz-porphyry, even-fine-grained)
VII. Salmi (Trüstedt, Timofeev)	?	?	←Pyterlite (ovoidal, "unmantled")	←Aplite-granitic dike rock

* A. Laitakari, "Palingenese am Kontakt des postjotnischen Olivindiabases," *Fennia*, Vol. L, No. 35 (1928).

Sweden, where there were repeated intrusions in the same fissures separated by erosion intervals, before it was made clear that basaltic

[30] T. Krokström, "The Hällefors Dolerite Dike and Some Problems of Basaltic Rocks," *Geol. Inst. Upsala Bull. 26* (1936), p. 113.

(doleritic) intrusions characterized the various geological (tectonic) events throughout Jotnian times.[31] Sederholm laid special stress upon the fact that the basaltic intrusions which are earlier than the emplacement of the oldest rapakivi are chemically somewhat different, being "ossipitic," from those which are later than the rapakivis, post-Jotnian in a broader sense, the latter being olivine- (auvergnose) or quartz- (camptonose) diabases (dolerites). A closer field investigation shows that, in general, there is no such contrast, the "ossipites" representing more deep-seated bodies which, therefore, are hardly comparable from a chemical standpoint of their potentialities with the other varieties (p. 355); moreover, the "post-Jotnian" intrusions when compared from area to area fail to confirm the regularity claimed.[32] A supposition that the "ossipitic" intrusions are of Noppi age (pre-Jotnian in broader sense, p. 347) seems inappropriate because they are neither associated with the sedimentary rocks of this system (e.g., the northwest Jaala subarea of the Viborg rapakivis, the southwest Ramsta subarea of Nordingrå), nor are they located below the true sub-Jotnian peneplain. The "ossipites" (gabbro, anorthosite, monzonite) of the Nordingrå area, as well as those of the Jaala subarea (Viborg area), thus belong to the Jotnian basaltic suite.

Real inclusions of basaltic rocks have been reported as occurring within the areas of rapakivi rocks. In contrast with the inclusions of older country rocks, which are nearly always grouped along the outer margin of the rapakivis, being located at or near the actual contacts, they have been encountered centrally within the rapakivi areas. Special attention has been paid to these inclusions in the Viborg area.[33] In the oldest granite phase (Lappee granite) they are for the most part strongly digested and appear as diffuse patches of green-colored rocks (tirilite) amid the otherwise brownish-red granite; the digestion is so complete that no essential chemical difference between the diffuse patches and the enclosing rock is to be detected apart from the slightly higher CaO content in the plagioclase of the patches. Other inclusions, which occur chiefly within the

[31] Von Eckermann, "The Jotnian Formation and the Sub-Jotnian Unconformity," *op. cit.*

[32] Sobral, *op. cit.*

[33] Hackman, *op. cit.*

later (ovoidal-pyterlitic and viborgitic) phases of rapakivi, are sharp-edged and of enormous size, their outcrops being measurable in square kilometers. These large inclusions have their doleritic texture well preserved, but, as a result of contact-metamorphic influence, they have generally been thermally altered to hypersthene rocks. They also show other minor chemical changes. There can be no doubt that the rock of these inclusions belongs to the basaltic series which is connected with the rapakivis, for, although the older country rocks do contain some basic igneous rocks, these are quite different structurally, texturally, and chemically from the inclusions under discussion. If these giant inclusions once formed intrusions within the older country rocks, is it not strange that there are no visible remains of the latter, in the form of vestiges of convection currents or other assimilation textures, associated with the margins of the inclusions? From analogy with the Hamra region of the Dalarne area it was postulated that the rapakivis of the Viborg area were intruded in, or replaced, different sections of the Jotnian sandstones. If this were the case, the aforementioned basic inclusions in the rapakivis may have formed dikes or minor sills within these sandstone sections, just as they do in the Dalarne area. Field observations showing that some of the inclusions have been completely digested (principally within the even-grained oldest granite phase) whereas others maintained a stronger resistance to digestion (within one of the latest phases) may be explained either by difference in the temperatures of the granite intrusion or by difference in the composition of the preceding basaltic (doleritic) intrusions (from which the xenoliths were derived), or by both factors. If the basaltic inclusions differed in composition, there is great probability that the basalts from which they were derived belonged to two different phases of igneous activity separated from each other in time and in stratigraphic position. On this latter interpretation the Viborg area conforms excellently with the other areas which provide evidence of (1) a phase of basaltic (or "ossipitic") intrusions prior to the emplacement of the oldest rapakivi granite (oldest porphyrites of the Dalarne area, gabbro of Nordingrå, "essexitic diabase" of Ragunda, "ossipite" of Åland and Nystad, gabbro of Jaala and labradorite-porphyrite of Hogland in the Viborg area), (2) several phases of

basaltic intrusions separating the successive emplacements of rapakivi granites, and (3) basaltic intrusions after the final rapakivi manifestations. In the Nystad area, for example, there are discordant dikes cutting conformable sills within the same stratigraphic section of the sandstone area, which consequently belong to two different periods of activity; there is also a basalt younger than one rapakivi phase, yet older than another rapakivi phase.

All these observations converge toward the single concept—that the basaltic activity is a special inter-Jotnian one which is in some way connected with the Jotnian Molasse tectonics, possibly as a post-orogenic readjustment of the Gothokarelids within their margins against older areas. The alternation that exists between the basaltic intrusions and the rapakivis points to some causal relationship and to a high crustal position for the rapakivis; moreover, the inter-rapakivi appearance of the basaltic intrusions indicates that the rapakivis themselves have a sheetlike form.

WEATHERING

The Finnish rock name "rapakivi" has been translated "rotten stone," but, as Eskola[34] has pointed out, an exact translation means "crumbly stone." Since the first publications on these rocks,[35] several authors have repeatedly returned to the problem of their weathering. In actual fact the coarse-grained (ovoidal "mantled") rapakivi, which has chiefly been considered, does not weather more intensely than any other coarse-grained or coarse porphyritic rock, as is evidenced by the magnificent embankments and other stonework constructions in Leningrad, which have successfully withstood exposure to the worst climatic conditions imaginable for more than a hundred years. It seems very inconsistent that the stone industry has with such persistence returned over and over again to these rocks for quarrying although warned against them in advance by their name (p. 344). Lately, however, it has been noted that the "weathering" is a special one, impossible to explain either by insolation, by exposure, or by present or past climatic conditions. Hori-

[34] P. Eskola, "On the Disintegration of Rapakivi," *Compte rendu Soc. Géol. Finlande*, Vol. III (1930), pp. 1–10.

[35] H. Struve, "Die Alexandersäule und der Rapakiwi," *Mém. Acad. Sci. St. Pétersbourg*, Vol. 6, No. 4 (6th ser., 1863).

zontal or nearly horizontal streaks or "schlieren," nearly flat regular bedlike bodies, or irregularly rounded patches, several meters in diameter, occur within the rock and are, moreover, perfectly fresh yet liable to crumble into angular gravel. In the case of ovoidal textural varieties the ovoids become concentrated within the vanishing detritus. This rock "disease" seems to affect most varieties of the rapakivi group, and there is no mineralogical or chemical difference between crumbled and fresh rocks. The crumbling (*moro* is the designation of this crumbling in Finnish) cannot be connected with any form of tectonic deformation because of its localized distribution and the fact that it is impossible to assign it to any general deformation plan. It seems probable that there is some interdependence between this crumbling and an indistinct, vaguely indicated bedding, which appears in field sections in the form of equidistant horizontal lines which are characterized by mineral concentrations differing from those of the general rock rather than by textural or qualitative differences between the individual beds. Even these horizontal lines, however, are by no means of tectonic origin but have arisen before the final solidification of the rock. The horizontal lines seem to be in some way connected with the horizontal parting of the rock (p. 344), which in its turn has no real connection either with tectonics or with the original cooling surfaces of the rocks. The rapakivis are explicitly post-tectonic but, even apart from this, the action of stress on even-grained or coarse-grained porphyritic rocks would give rise to crushed minerals or rock streaks. Such structures are, in fact, completely absent from the *moro*. If interpreted as crush breccia, the *moro* would stand completely unmatched. The *moro* disease of the rapakivi seems to be a more casual one, though it follows a law of some kind, otherwise the stone industry would have abandoned these rocks long ago.

A critical comparison of the *moro* with the normal fresh rock immediately adjoining it gives the impression that the final "cementing" material is lacking from the *moro;* the appearance is not as if the cement had redissolved but as if it had never been there. The *moro* has gone through the same evolution as the neighboring fresh rocks with the exception of the final cementation. The sporadically bedded appearance of the *moro* leads to the supposition that at some

early stage in the evolution of the rock certain parts of it were less permeable than others to the residual solutions and that these parts had a bedded form. The deficient permeability can hardly have been developed at higher temperatures during the former stages of evolution of the rocks. There must thus have existed some "pre-magmatic," rather pre-rapakivi, stage of evolution of the rocks. The rocks at this stage had a horizontal bedded appearance, and the individual beds, however uniform they may have been, had a somewhat different permeability (different grading?) with respect to (quartz-feldspar) residual solutions. The "schlieren"-like and rounded forms of *moro* bodies point also to differences of permeability within some porous pre-existing rock. The only rock formation that needs to be considered in this connection is that of the Jotnian sandstones. A discussion of the *moro* and its field appearance thus leads to genetic conclusions: that the rapakivi granites disclose a rheomorphic origin and have resulted from the granitization of different sections of the Jotnian sandstones. Consequently, they have originated under near-surface conditions which were favorable to the development of sheetlike forms, a conclusion independently reached in the course of the preceding section.

TECTONICS

Certain tectonic topics were discussed under the heading of "Structure." North-northwest faults are reported from the Hamra region of the Dalarne area which drop rapakivis of different ages to the level of the older floor rocks, thereby bringing them into different positions from their original ones and displacing them relatively to other rapakivi bodies of differing age. Most of the descriptions of the margins of the rapakivi against the older Archean rocks report that the boundary planes dip outward. If these boundary planes represent faults, which is probably the case, they are always older than the emplacement of the rapakivi, because the rapakivis and their small apophyses invade and penetrate the bordering wall rock. This is the case for the slightly convex western boundary line of the Ragunda area against the Archean; the gabbros and anorthosites which are clustered along the westerly dipping contact plane modestly intrude the older wall rock. In the Viborg area a broad outcrop of older

rocks, among rapakivi rocks, is bounded on the north by a fault which seems to be older than the adjoining rapakivi to the north. As has been shown (p. 345), there are no faults which limit and are younger than the rapakivi; the older Archean, locally dissected by faults, plays the limiting role. The mother-rock of the rapakivi (p. 357) has been considerably faulted, the final product only on a restricted scale. The first of these facts provides no indication as to the depth at which the rapakivi was formed. The second may indicate an original near-surface position for the rapakivis and moderate depths of solidification for the rocks.

Local crushing of the rapakivis, in connection with small faults and horizontal dislocations, may occur within the areas. They are of no importance in relation to the present discussion and only indicate block movements of the floor, a movement to which the youngest members of the Jotnian have reacted by wide folding with a north-northwest trend.

STRATIGRAPHY

It has been pointed out above (p. 347) that there is no possibility of exact stratigraphic correlation of the Jotnian sandstone sections from one area to another on the basis of either (*a*) their contents of, or association with, acid and/or basic magmatics, or (*b*) their textural and mineralogical development, or (*c*) the nature and age of the underlying floor rocks. The Molasse-like character of the Jotnian, with varying conditions of erosion and deposition, implies vertical movements, variable from locality to locality, which are rather dependent on their relative distance from older areas of stability or lability. Old labile areas, with prevailing negative tendencies, are most likely to harbor the most complete sequence of sediments, while negative tracts of positive areas, or tracts with preponderantly positive tendencies within labile areas, retain only accidental sections of sediments of quite uncertain and indeterminable stratigraphic position. So there is some probability that the fullest representation of the Jotnian will be found within areas where the Lower Molasse (the Noppi-Hoglandian) shows its greatest development (parts of the Dalarne area in the west, east of the Salmi area = Svir area?). If, moreover, the Noppi-Hoglandian sediments are reduced to insignificant erosional remnants (Hogland Island), or are

completely lacking (north of the Nystad area), the Jotnian section either rests with a small angular unconformity on conglomerates or rests with great discordance on an older floor, and its stratigraphic position is indeterminable. To correlate the different stratigraphic sections on a basis of different intensities of folding (the Jotnian having been broadly block-folded, with folds of small amplitudes striking north-northwest and dying away upward) is not possible because the intensity of folding varies from area to area.

One possibility, of relative importance, remains for determining the stratigraphic position of the various sections. The oldest sections are formed of detrital products which have come from a wider and more variegated denudation field (the gneisses and the more or less metamorphic sediments of the central Gothokarelian folded areas, with eventually some parts of the older Noppi-Hoglandian Molasse areas), whereas the later sections are built up chiefly of fragments of the earlier ones together with their enclosed and superimposed acid plutonics and/or volcanics. Consequently, the older the section, the richer it is in Fe, Mg, and Ca, while these constituents rapidly diminish in amount through the stratigraphic succession.

There is no reason to expect that granites should be present throughout the whole extent of every Jotnian area of thick sedimentary development. The possibility of granitic intrusion depends chiefly on the special thermal conditions. But if the Jotnian developed as outlined above (pp. 347–57) and if the acid magmatics entered the sandstones in the fashion already indicated (p. 357), or in some other manner, the magmatics may reflect, in their chemical and mineralogical composition the upward variation of the enclosing sediments. If they do, this must bear further witness to a high level of formation for the rapakivi granites.

TEXTURE

The rapakivi granites (i.e., the acid granitic magmatics) of the Jotnian areas of Fennoscandia are texturally essentially isotropic. There are no "schlieren" or parallel or even casual subparallel arrangements of elongated mineral components which could be interpreted as flow textures. Elsewhere within the ovoidal varieties rows

of ovoids appear in parallel arrangements reminiscent of fluidal textures; a closer examination, however, reveals the fact that these arrangements are not compatible with any general plan of fluidity and that they may reflect some pre-existing, pre-rapakivi features of the rock. If the grain of the rock diminishes at all along the outer boundaries, it does so only for a very short distance from the contact. Within the ovoidal varieties the ovoids decrease slightly in size and number toward the contacts, yet they do not stop at or in front of the contact plane but transgress it, being developed also in the wall rock. In the wall rock they are slightly sparser and they vanish at a short distance from the contact (e.g., the Buckholm locality). Parallel or subparallel alternations of somewhat differing mineral concentrations are suggestive of normal or foreset bedding rather than of flow textures. Veritable flow textures, found immediately at the contact, are exceedingly meager.

The textural varieties occurring within one and the same area are quite independent and well defined in the field; transitions between them do not usually occur. Textures of the kind that are described as characteristic of the upper part of veritable intrusive laccoliths or batholiths are completely lacking. With the exception of the true surface flows, the rapakivi granites, whether they be coarse- or medium-grained, or even porphyritic, have, as Eskola emphasizes, crystallized under ideally quiet conditions: after the first crystals appeared, there were no movements within the magma. The movements postulated by some authors to explain the mantled (and some unmantled) feldspar ovoids have left no textural vestiges within the rocks. The miarolitic and drusy textures, typical of some varieties, also bear witness against flow movements within the rock masses during the later stages of their development.

All these textural peculiarities, if interpreted according to customary premises, point to quiet crystallization under deep-seated conditions and, consequently, to the occurrence of high temperatures within the present outcrops of the rapakivi granites, i.e., to conditions of a somewhat batholithic kind, implying great thicknesses of cover. On the other hand, the assemblage of different textural varieties, occurring one inside another with relatively sharp boundaries, rather contradicts such an interpretation.

MINERALOGY

There are many mineralogical puzzles connected with this group of rocks. Only a few particularly characteristic ones can be mentioned.

It has been emphasized that the rapakivis are the only granites within Fennoscandia which are characterized by having orthoclase as the potassium feldspar, the older granites all containing microcline. This fact was referred to when classing these granites as postorogenic. The cases hitherto unmentioned where both microcline and orthoclase are reported to occur together within older rocks have been shown by Mäkinen[36] to rest upon incomplete determinations, the potassium feldspar in question being a microcline in which, as seen in certain sections, the grating structure was indistinct or lacking. Some rather even-grained rapakivis (e.g., the Tarkki granite) contain a perthitic orthoclase only, while others (chiefly ovoidal viborgitic) contain orthoclase and microcline in about equal amounts; for others again (the Väkkärä granite, rich in fluorite and topaz) prevalent orthoclase together with subordinate microcline are reported; pyterlite is reported to contain a perthitic microcline only. It seems probable that the microcline is relict yet without representing enallogenic inclusions of the ordinary type.

In miarolitic cavities, free-grown, long prismatic, low-temperature crystals of quartz with beautiful end faces are found, the roots of which do not grow out from the wall of the cavity but are anchored within the rock itself. In this case, also, there arises a suspicion that these are relict minerals with late aftergrowths.

These granites are nearly all exceedingly rich in fluorine, fluorspar and locally topaz (Väkkärä granite) being characteristic and regularly distributed constituents of the rocks. But there are no signs of "greisen" alteration in these rocks, although a fluor content is usually thought to be responsible for such alteration. An ordinary pneumatolytic action can hardly be connected with the appearance of these minerals.

In spite of their extremely varying bulk content of SiO_2, nearly all these rocks are characterized by intergrowths (more or less regular)

[36] E. Mäkinen, "Über die Alkalifeldspäte," *Geol. För. Stockh. Förh.*, Vol. XXXIX (1917), p. 121.

between potassium feldspar and quartz; syenitic, nearly quartz-free varieties also contain such intergrowths. The latter, which are "micropegmatitic" in their development, cannot be interpreted as representing eutectic residual solutions (p. 365); they are rather re-solution phenomena.

In some of these rocks an olivine rich in Fe (fayalite) is a characteristic constituent. Though fayalite, with about 7 per cent Fe in the melt, enters into a ternary eutectic with SiO_2 (tridymite) and sodium feldspar at 980°,[37] there are no eutectic textures associated with the fayalite, which is merely allotriomorphic against quartz and appears in moderately quartz-bearing as well as in quartz-free rocks. Its genesis is obscure, but it has perhaps something in common with the fayalite of the cavities in the obsidians of Yellowstone Park and elsewhere.

The mafic mineral components of the rocks are represented by pyroxenes (rhombic? and monoclinic), amphiboles (ordinary brownish-green, iron-rich, and hastingsitic), a ferric-ferrous biotite ("monrepite" var.) and a chlorite, one of these minerals being present, usually to the exclusion of the others, in any particular variety of rock. The occurrence of one or the other of the minerals as a characteristic constituent does not seem to be caused strictly by differences of the bulk chemical composition of the rock in question, variations in this respect being rather small. The appearance of a particular mineral within one or the other rock variant seems rather to depend upon temperature differences at the time of crystallization.

The mineralogical peculiarities touched upon seem to provide hints in two directions: (*a*) that the solidification (or crystallization) temperature of the rapakivis was rather low, i.e., that the rocks were formed at a high level; and (*b*) that crystallization took place under variable temperature conditions, i.e., beneath a cover of somewhat varying thickness. Further, they also indicate that rheomorphic processes played a part in the formation of the rock, under the conditions outlined. The conclusions are nearly the converse of those reached in the preceding section.

[37] N. L. Bowen, "Recent High-Temperature Research on Silicates and Its Significance in Igneous Geology," *Amer. Jour. Sci.*, Vol. XXXVIII (1931), p. 1.

CRYSTALLIZATION

The crystallization peculiarities of the rapakivi rocks are numerous. On various occasions they have been thoroughly investigated and discussed, particularly by Popoff.[38] There are three or four chief topics concerning them which have to be considered: (*a*) the "unmantled" ovoids and (*b*) the "mantled" ovoids; (*c*) the generations of constituents; (*d*) the quartz-feldspar intergrowths.

From the first the typical rapakivis have been regarded as characterized by big ovoids or rather ovaloids of potassium feldspar in a medium-grained somewhat uneven mesostasis of quartz, potassium feldspar, plagioclase, dark mica ("monrepite" var.) and/or hornblende and fluorspar, together with the customary accessory constituents—magnetite, zircon, apatite, and in some cases rutile and monazite (xenotime?). The ovoids rarely reach a size of 27 cm. in diameter, big ovoids, with a diameter of from 6 to 8 cm., are rather common, while ovoids with a diameter of from 3 to 4 cm. are the rule.[39] Lately, however, other textural varieties, even-grained or truly porphyritic rocks, have been classed with the rapakivis on the grounds of field geology and association. It has indeed been established that the ovoid rocks are rather subordinate and in some areas (especially in Sweden) almost completely lacking. It was also shown at an early stage that some of the ovoid rocks, over whole stretches of country, contain ovoids mantled by a compact ring of dark-greenish-gray plagioclase feldspar (oligoclase), this ring consisting of up to sixty or more short prismatic individuals arranged in crystallographic relationship to the central ovoid ("viborgites," Wahl). In other stretches of rock these rings are lacking ("pyterlites," Wahl), the rock being of a sensibly darker brownish-red color, and in contrast with the hornblende-biotite association in the former variety of ovoid rock containing biotite only; there is also a correspondingly lower CaO content. It is possible that these two varieties of rock represent different intrusion phases, though they were not separated

[38] B. Popoff, "Mikroskopische Studien am Rapakiwi des Wiborger Verbreitungsgebiets," *Fennia*, Vol. L, No. 34 (1938); "Ellipsoidische Einsprenglinge des Finländischen Rapakiwi-Granites," *Trav. Soc. Nat. St. Pétersbourg* (1897).

[39] Wahl, *op. cit.*

in the previous discussion (p. 359), nor does a separation in the field seem to have been attempted.

a) *The "unmantled" ovoids.*—The ovoids consist of perthitic microcline. The contours are in detail rough, with small pits. The border zone contains a string of idiomorphic quartz-crystals (margination texture). Quite exceptionally the ovoids develop traces of crystal form.

b) *The "mantled" ovoids.*—The ovoids consist of perthitic orthoclase and microcline perthite. The polysomatic plagioclase mantle (polysynthetically twinned according to the albite and/or pericline law) fits closely into the pits on the uneven surface of the potassium feldspar, being allotriomorphic against it but idiomorphic outward. The oligoclase is sometimes antiperthitic and contains minute scales of a colored mica which are arranged in three crystallographic directions within the oligoclase.[40] The potassium feldspar contains small idiomorphic plagioclase crystals. Among the mantled ovoids some individuals are found the cores of which, inside the mantle, consist of a granular mixture of the mesostasis minerals instead of a single potassium feldspar, this mixture being irregularly surrounded by an inner mantle of coarse potassium feldspar individuals, the whole being enclosed by the outer plagioclase mantle. More rarely two or three ovoids, without a plagioclase mantle, occur within this captured mesostasis, the association being encircled by the outer plagioclase shell. In some cases several concentric shells of plagioclase are observed, one inside the other.

Both types (*a*) and (*b*) have certain peculiarities in common. The core consists of one of the following: a single large individual; a Carlsbad twin; several large individuals, arranged in sectors; and several large individuals irregularly grouped together. In the last two cases there is no perceptible crystallographic regularity.

The ovoids, when more closely packed together mutually deform one another's boundaries, leaving rounded embayments, just as if they had been soft during their formation.

The potassium feldspar ovoids contain concentric rings of inclusions of all the minerals of the mesostasis; up to ten such rings have

[40] Popoff, "Mikroskopische Studien am Rapakiwi des Wiborger Verbreitungsgebiets," *op. cit.*

been reported, and these rings of inclusions reproduce all the embayments noted above and never indicate crystallographic faces. Occasionally they are somewhat eccentric. The quartz grains of these rings are rounded; hornblende and biotite are mostly idiomorphic. Bigger inclusions consist of aggregates of mafic minerals together with rounded quartz and fluorite, or of quartz alone, in well-rounded grains.

Besides the independent inclusions of well-rounded quartz, inclusions of the same sort occur with rather rectilinear or concave contours; these are intergrown with the enclosing feldspar in a manner reminiscent of pegmatitic feldspar-quartz intergrowths.

If the ovoids are supposed to represent real phenocrysts, i.e., early products of crystallization, the last-mentioned item indicates that they consolidated at low temperatures—a deduction which is hardly compatible with early crystallization (in the usual sense) in such surroundings. The large dimensions of the ovoids suggest, on the contrary, a considerable depth of crystallization. The ovoidal form points to resorption, and, indeed, the manifold inclusion rings suggest repeated phases of resorption. Both the rounded quartz inclusions which are independent of the rings in the central parts of the ovoids and the idiomorphic plagioclase inclusions are witnesses of preexisting quartz and plagioclase, which crystallized prior to the investment of the ovoids. The customary way of explaining these peculiarities appeals either to very unstable and changing (rising) temperatures or to irregular oscillations of vapor pressure during the "intratelluric" period of crystallization; these peculiarities point, however, to no "intratelluric" condition but rather to a high level of rock consolidation. Moreover, the rapakivis are always reported as having been formed from very "dry melts," since no evidence of considerable pneumatolytic action is known. No routine explanation based on the usual conceptions of "magmatic" behavior satisfies all the implications disclosed by close examination of the ovoids, to say nothing of the ovoids containing central mesostasis or of the inclusions of mafic minerals associated with quartz and fluorite.

c) *The generation of constituents.*—Excepting the accessories, all the mineral constituents of the rapakivis, whether the latter be grained or porphyritic, are represented by two generations; the early

crystallization of quartz especially being characteristic of all known varieties. This feature should mean a repeated undercooling of the "magma" during the course of crystallization, i.e., conditions of consolidation at or near the earth's surface. The question now arises, "How can this lowering of temperatures be reconciled with the repeated rising of temperatures demanded by the acts of resorption?"

d) *The quartz-feldspar intergrowths.*—Quartz-feldspar intergrowths of the "micropegmatitic" type are very common both in the ovoidal and in the even-grained rapakivis. In the first-named variety micropegmatite appears (1) within the cores of ovoids, (2) independently thereof at the junction of the plagioclase shell and the core, and (3) within the mesostasis. In the even-grained rocks it also appears in different generations, while a later crystallization of quartz and potassium feldspar also occurs in which the two minerals are independent of each other. The "micropegmatite," indeed, cannot represent a crystallization from a residuum. Its occurrence, however, implies low temperatures, i.e., a high level of consolidation. In the examples presented by the rapakivis the micropegmatite may represent corrosion phenomena, as suggested long ago for other combinations by Schaller. It may be pointed out that its recurrence is thus irreconcilable with true surface conditions. Its repeated appearance, moreover, awakens a suspicion that the course of crystallization has been repeatedly inverted.

CHEMISTRY

The rapakivis have a distinctive chemistry of their own. Mineralogically they fall for the most part within 226P of Johannsen's[41] classification; only part of them, especially those of Sweden and of the bottom of the Bottnian Gulf, sensibly belong to 216P. Johannsen describes them as abnormal amphibole-biotite-granites. Chemically, they are distributed within the calc-alkaline suite as well as within the potash suite of Niggli.[42] In the former suite they represent the engadinite-granitic (3, pyterlite, *partim*) and the yosemite-granitic (4, viborgite) types within the leucogranitic "magma" (*a*); the

[41] A. Johannsen, *A Descriptive Petrography of the Igneous Rocks* (Chicago: University of Chicago Press, 1932), Vol. II, p. 243.

[42] P. Niggli, "Die Magmentypen," *Schweiz. Min. u. Petr. Mitt.*, Vol. XVI (1936), p. 335.

tasna-granitic (2) type within the granitic "magma" (*b*); the natron-rapakivitic (6, the greater part of the Swedish rapakivis are of this type) and leucoquartz-dioritic (7, tirilite, *partim*) types of the trondhjemitic "magma" (*d*). In the potash suite they fall within the rapakivitic (1) and granosyenitic (2) types of the leucosyenite-granitic "magma" (*a*). They are characterized by a wide range of silica content; a high percentage of iron oxides; dominance of potash over soda, especially in the east; a very low MgO content throughout; and varying amounts of CaO. Some of these rocks contain the greatest amount of fluorine known within granitic rocks.

This wide range of distribution within the Niggli system of classification, which would perhaps become even wider if recent analyses of their volcanics were also considered, is the more surprising as the rapakivis have always been regarded as the most uniform and homogeneous suite of rocks known in Fennoscandia. The variability depends partly on the wide range of silica content; but, as the quartz grains (brownish to black, rarely reddish or bluish) are megascopically inconspicuous, the fluctuations of silica are hard to visualize. The variability also depends on other circumstances, as shown by the representation of the rapakivis in both the calc-alkaline (Pacific) and the potash (Mediterranean) suites of rocks. It has been shown (p. 368) that the crystallization of free silica as quartz has little or no influence on the development of the other constituent minerals. Just as the iron oxides are uniformly high throughout the whole suite, so the magnesia is extremely low; together these constituents seem to be of little or no importance for the evolution of rock variability. The variability of the suite is accounted for principally, or entirely, by the relative proportions of CaO, Na_2O, and K_2O; i.e., by the content of potassium feldspar and plagioclase, and by the composition of the latter.

There are about fifty modern analyses of rapakivis available, of which about twenty represent the Swedish examples, whereas about thirty are of rapakivis from the areas in Finland. In view of the foregoing statements and with the object of making the analyses directly comparable, the CaO-Na_2O-K_2O contents of the analyses have been recalculated relative to 100 per cent SiO_2. The molecular proportions of CaO, Na_2O, and K_2O so obtained were then reduced

to percentages, and these molecular percentages plotted in a CaO-Na_2O-K_2O triangular diagram (Fig. 2). The projection points show a somewhat marked localization and symmetrical distribution within the lower half of the triangle. CaO and Na_2O show a roughly equal amplitude of variation, while the variation in K_2O is a little more

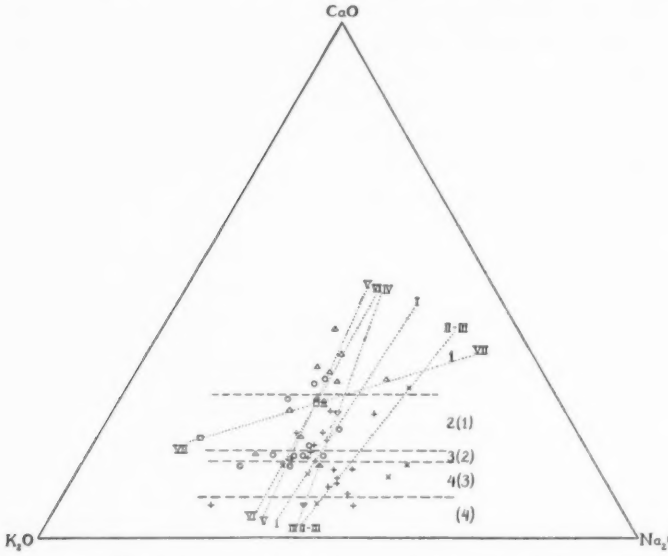


FIG. 2.—Molecular percentage of CaO–Na_2O–K_2O referred to 100 per cent SiO_2 within the Rapakivi granites of Fennoscandia. *I*, Dalarne-Hamra area (+). *II–III*, Nordingrå-Ragunda area (×). *IV*, Åland area (▽). *V*, Nystad area (○). *VI*, Viborg area (△). *VII*, Salmi area (□). Tentative stratigraphical sequence 1 (oldest)—4 (youngest).

pronounced. The Swedish rapakivis are decidedly more sodic than the Finnish ones, as Eskola[43] has already pointed out. If straight lines now be drawn parallel to the K_2O-Na_2O base of the triangle at 28, 17, 15 (and 8) CaO, it is found that the projection points falling in the fields delimited by these lines roughly correspond to the groups 1, 2, 3, and 4 of the tentative sequence tabulation of the

[43] "On Rapakivi Rocks from the Bottom of the Gulf of Bothnia," *op. cit.*

rapakivi associations (pp. 350 and 360), the highest CaO contents corresponding to the earliest ones and the lowest to the latest ones. The several points representing the rocks of individual areas share a common peculiarity: the later the rock, the higher becomes the K_2O content; the Na_2O content remains more or less constant for the rocks associated within each area, since the projection points for individual areas are arranged in strips which are either parallel to the CaO-K_2O side of the triangle or converge slightly in the direction of the 100 per cent K_2O-point.

According to the usual fashion of interpreting analyses, this would mean that each of the rock sequences represents a "normal" differentiation series, with accumulation of the constituents of orthoclase feldspar and quartz in the end products. A closer examination of the rocks associated within each area reveals, however, that such cannot be the case, because one remains completely without evidence as to where this differentiation could have taken place (p. 375). Moreover, there is no systematic concentration of mafic minerals within the "first fractions" (e.g., the nearly constant contents of $Fe_2O_3 + FeO + MgO + TiO_2$ throughout the rocks of each association); furthermore, the specific gravities of the dominant minerals (quartz, orthoclase, and plagioclase within the range albite-oligoclase) are too closely similar to allow of gravitational segregations; finally, textural, mineralogical, and crystallization details, such as have been pointed out in the preceding sections, are completely at variance with such a mode of rock evolution. In this connection it may be emphasized that the variation of quartz content of the rocks is irregular throughout the whole projection field and shows no essential increase toward the base of the diagram. The whole rock suite is quite "abnormal," as Johannsen has already recognized.

The chemical diversity within such a seemingly homogeneous group of rocks, amenable as it is to indistinct laws, despite the apparent irregularity of the rocks when inspected in the field, indicates a genetic dependence which, on the customary mode of explaining the rocks as "magmatics," can be related neither to a deep nor to a shallow original position within the earth's crust.

DIFFERENTIATION

Sederholm[44] always emphasized the uniform homogeneity of the rapakivis. When grouping the rapakivis together as the fourth (last) group of the pre-Cambrian granites of Fennoscandia, he seems to have believed that the rapakivis, after a long-lasting differentiation history within the primordial "magma basin" throughout the pre-Cambrian times, had lost their ability to differentiate further, so that they thus represent a sort of final stage or acid end product. Even Wahl and Hackman, although recognizing the limited diversity of the rapakivis, as shown above, are fully aware of their essential homogeneity within the separate areas. Eskola[45] speaks of the rapakivis of Sweden as having a wider range of differentiation than those of Finland. Yet as regards the basaltic rocks which are always associated with the rapakivis, Sederholm[46] held them strongly apart from the rapakivis proper; he drew a distinction between (*a*) a basic group older than the rapakivis: the "ossipitic" suite of rocks and their differentiation products (anorthosites and monzonites, on the one hand, and pyroxenitic rocks, on the other); and (*b*) a basic group younger than the rapakivis: the doleritic suite of olivine-(Åsby-) diabases and quartz-diabases (p. 353). He did not deny the close *geological* relationship of these three groups of rocks, but he never tried to derive one group from another, despite the many temptations to do so offered by field association.

Wahl[47] was the first who tried on a grand scale to reconstruct the conditions which might have been responsible for the evolution of the rapakivis from the magma of the basaltic rocks with which they are, for the most part, geologically associated; following earlier suggestions of Yakovlew,[48] he introduced into the petrological thought

[44] "Über die finnländischen Rapakiwigesteine," *op. cit.;* "On Orbicular Granites, Spotted and Nodulated Granites, etc., and on the Rapakiwi Textures," *Bull. comm. géol. Finlande*, No. 83 (1928).

[45] "On the Rapakivi Rocks from the Bottom of the Gulf of Bothnia," *op. cit.*

[46] "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *op. cit.;* "On the Geology of Fennoscandia, with Special Reference to the Pre-Cambrian," *op. cit.*

[47] *Op. cit.*

[48] S. A. Yakovlew, "Granitoid Veins within Dolerites of the Southwestern Coast of Lake Onega" (in Russian), *Trav. Soc. Nat. St. Petersbourg*, Vol. XXXIII, No. 5 (1903).

of Fennoscandia the principle of "contrasted differentiation," hoping thereby to explain these abnormal rocks and their origin. Yet, as he had also to explain the strange textural, mineralogical, and crystallization peculiarities of the rapakivis, he was forced to postulate not only very complicated conditions of deep-seated magma chambers but also repeated changes of temperature-pressure conditions and complex flow movements during the evolution of the rocks and their emplacement. In support of these postulates, neither geological evidence nor textural indications are to be found in the field; indeed, opinion is unanimous that the rapakivis evolved under extremely quiet conditions of geological setting and crystallization.

Von Eckermann[49] lately proposed a similar mode of explanation. Yet, as he was aware of the insurmountable difficulties presented by the said textural peculiarities to such a genetic explanation, he simply abstracted part of the evidence from the whole, declaring that in the field the specially troublesome rocks played a quantitatively subordinate role. When it is realized that this rock suite was originally defined precisely in terms of the aforementioned peculiarities and that von Eckermann omits to consider mineralogical observations of his own with reference to similar peculiarities in the rocks of his special investigation, his abstraction, to say the least, seems strange. Furthermore, he tries to corroborate the hypothesis of "contrasted differentiation" with respect to the basalt→rapakivi association of Fennoscandia (p. 353) by a great number of new analyses, and by constructing from them a series of variation diagrams based on Niggli values. It is true that these analyses conspicuously reduce the gap existing between the two supposed, highly contrasted, end members. But smooth lines, even of a very great number of diagrams, do not prove the supposed course of evolution, if geological and other indications are not also in accord with such a continuous evolution. All they can demonstrate is that the rocks under consideration may have evolved under similar geological conditions and may have assumed their final chemical aspect within a similar geological milieu. Besides the difficulty of the typical textural peculiarities referred to above, which are markedly at variance with the supposed mode of evolution, it must be emphasized that

[49] "The Jotnian Formation and the Sub-Jotnian Unconformity," *op. cit.*

the squeezing or "filter-press" action, which Bowen[50] cites as one of the chief stimulating factors, if not the only one, of the process promoting "contrasted differentiation," is completely lacking within the Fennoscandian rapakivi areas. In their geological position and their "magmatic" evolution the rocks of the rapakivi suite are entirely post-orogenic; as to this, all investigators are in accord. No orogenic stresses were available to effect the squeezing, i.e., to induce the "contrasted differentiation" on the grand scale which the field distribution of the rocks demands. Even if the existence of the supposed transition rocks between the true rapakivis and the "ossipitic" or doleritic series be taken into account, a closer examination of the smoothed and generalized curves in the variation diagrams of von Eckermann[51] reveals a distinct chemical discontinuity between the rapakivis proper, on the one side, and the rocks geologically (and chemically) appertaining to the "ossipitic"-doleritic series and their associates, on the other. The smoothed curves completely hide these discontinuities. Above all, a mineralogical (and textural) discontinuity still exists in every case, even where the silica contents of two neighboring members in the diagrams may be closely similar: the representatives of the doleritic side contain labradorite, or exceptionally, when not specially albitized, andesine; whereas on the rapakivi side the feldspar ranges from oligoclase ($Ab_{80}An_{20}$) down to albite. The locally very much variegated "ossipitic"-doleritic association, which provides the "transition rocks," has created the confusion. Although these also represent a "Molasse" type of magmatic activity, they are always separated from the rapakivis proper by a marked time hiatus. In the Viborg area these troublesome "transition" rocks are represented by the Jaala subarea where they are of somewhat earlier emplacement (deep-seated gabbros with monzonites, anorthosites, pyroxenites, and titaniferous iron ores) and by the island of Hogland in the southwest (various extrusives of the labradorite-porphyrite group, more or less femic); in the Dalarne area (Hamra subarea) by the extrusive and hypabyssal

[50] "Crystallization-Differentiation in Igneous Magmas," *Jour. Geol.*, Vol. XXVII (1918), p. 394.

[51] "The Loos-Hamra Region," *op. cit.*, pp. 289, 323; "The Jotnian Formation and the Sub-Jotnian Unconformity," *op. cit.*, p. 28.

porphyrites and monzonites (embracing adamellose, shoshonose, hessose, andose, camptonose, monzonose, and harzose in the C.I.P.W. classification); in the Nordingrå area by the deep-seated gabbro of the southwest field (with anorthosites and monzonites) and by the eastern, much later ("post-Jotnian") hypabyssal dolerite (auvergnose) dike (with associated rocks of adamellose = adamellitic, shoshonose = kentallenitic, hessose = anorthositic, andose = kentallenitic, tonalose = monzonitic-banatitic, custerose = peridotitic and titaniferous iron-ore composition in C.I.P.W. and European terms). The other rapakivi areas may contain similar associations with a smaller range of diversity, but as yet these are not completely known, as they have not been described in detail.

The repetition of nearly identical series of rocks at different levels and in consecutive time intervals within the same area raises nearly "supernatural" conditions with regard (*a*) to the magma basin, if there had been one; (*b*) to the temperature fluctuations; (*c*) to the crystallization possibilities; and (*d*) to the rising and sinking movements which would be essential to the effective operation of crystallization differentiation. The conditions, if reconstructed to act continuously, are seen to counteract one another, and no regularities comparable with those found in the field could be expected to result from crystal differentiation. Moreover, there are conditions of shallow position and of quiet crystallization to be satisfied, in accord with the conclusions already drawn as to the rapakivis proper; such conditions are incongruent with those indicated above. Finally, the disproportion between the great extent and the considerable volume of the rapakivis proper and the relatively small occurrences of their supposed parent rocks, even after the repeated operation of the desired and supposed evolution, raises serious doubts, in this case, as to the possibility of such a course of rock derivation. In this direct genetic sense the true rapakivis must be regarded as independent of the "ossipitic" and doleritic rock suites. It should perhaps be added that the compositions of all the rocks concerned fall within limits which exclude every possibility of differentiation by liquation.

Nevertheless, there may be some mutual interdependence between the rapakivis and the associated doleritic rocks (including

their variegated derivatives), although this interdependence may be of some other kind than has hitherto been visualized.

FORM OF ROCK BODY

Never, I suppose, has there existed such a diversity of opinions about the form of body of any well-defined rock massif as in the case of the rapakivis.

The idea of surface lava sheets, perhaps the earliest one, was suggested by the indications of upper flatness of the rapakivi areas, by the gentle slopes conforming with the older surrounding peneplain, and by the constant height difference—though varying from area to area—above this peneplain (p. 343). This idea was early abandoned but lately it has experienced a revival[52] in a modified form to the effect that the granitic rapakivis may have solidified beneath a cover of their own lava sheets; thus they are regarded as representing the deeper parts of the extrusions. This idea was based on field experience in the Dalarne (Hamra) area, where cognate extrusive lava sheets occur together and seemingly intermingled with granitic rapakivis. Apart from the facts that the course of denudation and the disintegration of the rock formations (as registered by the coarse conglomerates and sandstones intercalated between the rapakivi units) and the rough relief thereby required and implied by the detrital deposits do not conform with such an explanation, there are two weighty arguments against the idea of surface sheets: (*a*) it is impossible to apply it to the other areas, explicitly those of coarse or giant textures, and (*b*) the regular and broadly spaced jointing (p. 343) is inconsistent with the field appearance of superficial lava sheets. It follows from these considerations that it is necessary to separate, in the discussion of form of body, the true lava sheets, with their flow textures and irregular narrowly spaced jointing, from the granitic bodies, which are free from any signs of internal flow movements. The uniformity of appearance of the rapakivis within the different areas implies, moreover, similar form of body throughout.

The representation of the rapakivis as laccolithic bodies was first adopted for the Ragunda area.[53] It was then extended to the Viborg

[52] Von Eckermann, "The Jotnian Formation and the Sub-Jotnian Unconformity," *op. cit.*

[53] Högbom, *op. cit.*

area[54] and thence regarded as valid for the other areas also. The laccoliths may have been very thin and flat in comparison with their areal extensions. This interpretation was based on the observation of a very flat floor in the Ragunda area, and also on the recognition of what were explained as erosion holes ("false windows") within the interiors of rapakivi areas, i.e., well-spaced occurrences of large areas of Archean rocks surrounded by rapakivis and independent of the outer boundaries of the area of younger rock. Such occurrences might thus represent the fairly uneven floor of the laccoliths, yet locally they were interpreted as roof pendants.[55] In consequence of this, two different opinions arose: (*a*) the supposed laccoliths were intruded at a considerable depth below the crustal surface of that time,[56] and several thousand meters of the roof rocks have been removed by erosion since the time of their emplacement, i.e., before the late Jotnian; (*b*) they were intruded at a shallow depth, beneath a comparatively thin cover of Archean country rocks.[57] Apart from the fact that within the rapakivi areas neither structural nor textural signs are found which can be interpreted as characteristic of laccolithic intrusions, the first opinion does not agree with the field observation that a post-Gothokarelian erosional plain, not far distant from the Eparchean one, passes beneath the rapakivis (p. 343). The same argument is valid against the second opinion; moreover, there exists no horizontal parting in the Archean which would favor the development of such a form of intrusion and of body. Identical arguments are opposed to the representation of the rapakivis as lopoliths. If these terms be applicable to the rapakivis, their location should be restricted to certain horizons of the Jotnian sandstone formation, i.e., as very flat bodies at a rather shallow depth (pp. 343, 347, 357, 360).

The rapakivi bodies have also been designated as taphroliths. Even for this form of body the restrictions as to position mentioned above should be valid. This designation is maintained on the observation of outwardly dipping contact planes and on the interpreta-

[54] Wahl, *op. cit.* [55] *Ibid.*

[56] Sederholm, "On the Geology of Fennoscandia, with Special Reference to the Pre-Cambrian," *op. cit.*

[57] Wahl, *op. cit.*

tion of these parting planes as being older than the rapakivis themselves (p. 359). The "grabens" (troughs), however, may have been very shallow, so that they did not conspicuously disturb the older peneplain (p. 359). The rapakivi infillings may have been comparatively thin (p. 345) and the subsequent course of denudation conformable with that of the areas outside the troughs.

The idea of a batholithic form of body (pp. 344, 345) has lately been advanced again[58] despite its many difficulties. Apart from a number of weak "pros" and strong "cons" mentioned in the previous sections, there is one supposed evidence which was interpreted in the Viborg area as proving a batholithic form of body: the big "false windows" of Archean rocks which were regarded as "roof pendants." A closer examination of these "windows" shows that in their southern row the Archean rocks share an east-west strike and a steep dip with the Svecofennides outside the rapakivi area; there is no deviation of direction or different association of rocks, and their structures and textures are similar to those of the true Archean. This southern row of "windows" is separated from a more northerly one by a fault older (?) than the latest rapakivis. In the northerly group of "windows" the Archean complex comprises a different association of rocks; their disposition is also steep and they strike in the north to north-northwest Gothokarelian direction. Recent drill holes in one of the "windows" (one which is represented by the Ihalo limestone quarries) have penetrated to considerable depths (more than 220 meters) without striking the rapakivi of the supposed batholith underneath. The depth of drilling is, moreover, considerable even if the rapakivi be regarded as a sheetlike body. That the Archean areas considered cannot represent roof pendants is even better demonstrated by the facts that elsewhere they are penetrated from above by rapakivi veins[59] and show but slight thermal changes of posttectonic age. They therefore represent the floor and thus give an idea of how slight the metamorphic changes may have been beneath a considerable covering of rapakivi even in its central part. In this connection the coexistence within the same area of three or four rapakivi variants, differing one from another not only in texture and

[58] Hackman, *op. cit.*

[59] Wahl, *op. cit.*

chemistry but also in age (pp. 347, 361, 368), raises insuperable space difficulties for a batholithic emplacement; far more difficult, then, would be a monogeneous emplacement of a single body with dimensions corresponding to the respective areas. The observations that certain contact planes dip outward are worthless and unconvincing as proof of a batholithic form because they refer to only a few meters of section and are therefore ambiguous.

EMPLACEMENT

The form of body of a plutonic rock or rock suite is always connected with and resolves itself into the question of its emplacement. The various forms of body ascribed to the rapakivis have been discussed above, and none of them is found to satisfy all the observed field conditions. It may be summarily stated that the rapakivis develop sheetlike flat forms of horizontal position: as to this, most recent investigators are in accord. Furthermore these sheetlike bodies are situated above the Eparchean peneplain and above another minor inter-Molasse denudation plain which cuts the early Molasse sediments of the Gothokarelian, i.e., the Noppi-Hoglandian formation and its associated volcanics. They thus intervene within the Jotnian sandstone sediments, and, consequently, in accord with customary thought, they may tentatively be designated as mighty sills intruded in and intercalated between these beds. Yet the emplacement presents difficulties. The sedimentary cover of each intrusion was never of specially great thickness; how, then, was the plutonic magma that forced its way from the "great depths" arrested at such an inconsiderable distance from the surface of that time? An intrusive sheet of such a form and at such a high level should have been already crowded with inclusions at the moment of its horizontal spreading, the more so, indeed, when forcing its way between comparatively friable beds of sandstone. The rapakivi sheets have always been described as completely free from inclusions, apart from occasional marginal examples consisting of ancient rocks. How was it that, instead of continuing to the surface, the "intrusive magma" spread horizontally through widely extensive areas beneath a thin covering of sandstone? If it was able to digest casual sandstone inclusions, it would surely have had sufficient potential energy

to overcome this last obstacle. If such an acid and viscous magma were forcibly injected between the sandstone beds it should have retained textural vestiges of its movements; but there are none.

No feeding channels for the rapakivis are known. Two long and large dikes occur south of the Jaala area, within the older floor, but these cannot be reckoned as feeders because they are composite dikes of basalt and quartz-porphyry, and therefore they cannot have produced rapakivi of the normal type; this conclusion also applies to other porphyry dikes within Jotnian sandstone areas. It may be stated that the more the rapakivi areas are reduced by erosion, the more their circumferences approach circular outlines (subarea of Tulomajärvi, east of the Salmi area).[60] If this observation is not accidental, it suggests the idea of pipelike feeding channels. Sederholm[61] has described small circular occurrences of granites of his third group (early Molasse granites of the Gothokarelides) which he considered to be the feeding channels (Mosshaga, Åva) of larger areas; however, a closer inspection of these areas makes it clear that no massive flow of magma can have passed through these channels, since structural elements of the ancient (Archean) wall rock, such as dikes, project into the channel areas and yet have undergone only slight metamorphic and mechanical alterations, the channel being crowded with relics from the older wall; a massive flow of magma, whatever its transporting capacity might be, while delivering magma to the rapakivi massives above the Eparchean peneplain, would inevitably have cleansed such a channel completely of these remains. Such considerations rather imply that a sort of upward diffusion was active for some time and produced "igneous" rocks at higher levels during the early Molasse phase. Such a diffusion action presupposes complete solidity of the rock traversed. One is again tempted to suggest some such process when facing the question of the final emplacement of the rapakivis. Indeed, all the field evidence and data relevant to the rapakivi sheets point to one and only one way out: that the sheets may have replaced extensive tracts and thick formations of the Jotnian sandstones and the Archean close by.

[60] V. M. Timofeev, *Petrography of Carelia* (in Russian) (Leningrad, 1935).

[61] "On Migmatites and Associated Pre-Cambrian Rocks of Southwestern Finland," *op. cit.*

GENETICS

The question of the rapakivi emplacement has thus resolved itself into a question of replacement. Before entering upon a discussion of the delicate processes which may have led to the formation of the rapakivis, it may be convenient to devote a few words to the basaltic aspect of the Jotnian vulcanicity.

Nearly twenty-five years ago, Sobral,[62] as a result of excellent and thorough field and laboratory investigations, pointed the way toward a solution of the problem involved. Unfortunately, even up to the present day his suggestions have not earned the attention they merit, perhaps because the promised Part II of his investigations has never, to the writer's knowledge, appeared, perhaps because the published first part appeared outside current geological periodicals, perhaps also because it appeared too early, at a time when petrological thought was dominated by the differentiation theories then flourishing. From Sobral's investigations (pp. 353, 372) it is evident that the diversity of magmatic rocks associated with the Jotnian basalt (dolerite) suite ("differentiation series") depends (*a*) on the environment in which the basalt (dolerite) was intruded and (*b*) on the thermal potentialities carried upward into the higher levels of the crust by or with the rising basaltic magma. The first condition was proved, *inter alia*, by the simple observation that the latest basalt dikes, when cutting the rapakivi, become quartz-bearing, whereas when cutting the older dolerite dike they are olivine-bearing. Even more convincing proofs are provided by a comparison of the older ("post-Jotnian") Ulfö dolerite dike in the east with the oldest ("sub-Jotnian") gabbro in the southwest and their respective associates. Both belong to the Jotnian formation in the broader sense and lie frankly above the Eparchean peneplain, although at present they represent sections exposed at different levels, the older one having been eroded to a conspicuously greater depth. Thus the latter is older than any rapakivi granite present, whereas the former not only is younger than the extensive granitic areas but is also younger than the superimposed arkose of weathering and the uppermost discordant Jotnian sandstone (Jotnian in the narrower sense).

The Ulfö dike contains irregular and subangular streaks of perido-

[62] *Op. cit.*

tite, titaniferous iron ore, and anorthosite, the relation of which to the enclosing dolerite is obscure; besides these there are numerous inclusions of the wall rock, i.e., of rapakivi granite, in all degrees of transfusion, varying from sharp-edged fragments to vague patches, "schlieren," and streaks; these represent the whole diversity of rocks enumerated on page 375. Inclusions of the Jotnian sandstone are generally transfused to rocks grading into monzonite. The mineralogical effects of the transfusion can be followed up in detail and chemical analyses of the most typical stages are also available. Besides an immigration into the inclusions of femic oxides (including CaO; as molecules or ions?)[63] and an emigration of SiO_2 with minor quantities of Al_2O_3 (with some K_2O?), there develops a remarkable change in the proportions of the alkalies which is incompatible with a simple melting: the normative proportion Ab:Or = 9:11 (within the unaltered rapakivi) rises to 4:1 (in the kentallenite) and to 13:1, and even as far as to 26:1 in the ultra-salic veins. The latter, representing the partial transfusion products from acid inclusions and neighboring wall rock, elsewhere actually cut the dolerite, within which the original norm proportion is Ab:Or = 1.7:1. While the "emanation"[64] of the femic oxides (with CaO) seems to migrate within the confines of the wall of the dike, the Na_2O emanation (with some CaO?) transgresses the contact planes, tends to migrate into the wall rock, and, in any case, proceeds farther or faster. The problem of space connected with the immigration of elements seems to play a subordinate role and to find its solution by flow (in the earlier stage of solidification of the dolerite), as indicated by textures and by lenticular arrangement of the xenoliths; or elsewhere (at a late stage), by transgressive veins. The porphyrites of the Hamra-Dalarne area, whose diversity of purely supracrustal rocks is nearly identical with those of Nordingrå (p. 374), may have been formed under quite similar conditions.

[63] A. Holmes, "A Contribution to the Petrology of Kimberlite and Its Inclusions," *Trans. Geol. Soc. So. Africa*, Vol. XXXIX (1936), p. 379; D. Reynolds, "Demonstrations in Petrogenesis from Killoran Bay, Colonsay," *Min. Mag.*, Vol. XXVI (1936), p. 367; "The Eastern End of the Newry Igneous Complex," *Quart. Jour. Geol. Soc.*, Vol. XC (1934), p. 585; C. E. Wegmann, "Zur Deutung der Migmatite," *Geol. Rundschau*, Vol. XXVI (1935), pp. 305–50.

[64] Holmes, *op. cit.*

Within the older gabbro field of Nordingrå the monzonitic rocks which grade into the gabbro without sharp boundaries may also have originated in a similar way at the expense of older Jotnian sediments. Yet, as the gabbro represents a lower level of emplacement, the correspondingly greater thermal reserves which were developed may have co-operated toward a wider dispersion of the complex "emanations" outside the original walls of the intrusive body; the permeability of the sediments, then relatively fresh, may have contributed to this relative ease of migration. The coarse-grained anorthosite which occurs in large masses in this part of the area may conceivably have originated in some similar way, since its field position, coarse textures, peculiar composition, and considerable volume are all hard to bring into accord with any differentiation process at the expense of the gabbro. There is no need, however, to enter into details in this connection. Moreover, as the foregoing discussion discloses, there are two "ossipitic" suites of different ages within the Nordingrå area, again providing a proof that this association is not a conclusive index of age. Furthermore, the discussion makes it clear that no rocks of true rapakivi composition can be referred to the operation of this act of transfusion, since even the most siliceous rock veins in the "ossipitic" suite are completely different in chemical details, being extremely high in Na_2O (and CaO) and extremely low in K_2O.

The process whereby the rapakivis came into being as replacements of different formations of the Jotnian sandstones (and the adjoining Archean rocks) is by far the more complicated because it involves enormously larger masses at a relatively high crustal level. It also involves the necessity for accounting for the emigrating elements which possibly accompanied the "transfusion." In the case of the dolerites mentioned above, where only minor masses at a lower level are concerned, the outward migrating elements may in part have found their outlet in the late acid veins, i.e., by an increase of volume. Therefore, there are two possibilities to consider: (*a*) the replacement may have occurred without any considerable volume change and (*b*) it may have been accompanied by a perceptible increment of volume. The first possibility corresponds to the "deep-seated" rapakivis which are free from traces of flow movements acquired during their emplacement;

the second may be considered in connection with the extrusive rapakivi bodies.

a) *Replacement without any considerable volume change.*—A revision of all detrital formations shows that the Molasse sediments are characterized by the highest percentage of porosity known, especially in their sandstone members which were rapidly accumulated under short yet turbulent conditions of transportation. The Old Red and New Red sandstones, together with Tertiary Molasse sandstones, are representative in this respect. Measurement of a Lower Carboniferous sandstone, belonging to the Upper Molasse of the Caledonides of East Greenland revealed a porosity of 12 per cent and more, the rock having been considerably cemented in later Mesozoic and Tertiary times as compared with its first diagenetic consolidation. Moreover, such sandstones are often developed as mighty sheets with well-spaced bedding planes and a rectangular system of vertical joints which are so broadly spaced as to form giant freestones. A sporadic content of $CaCO_3$ and of cementing limonite in various amounts such as is characteristic of these rocks may raise their potential porosity, either as a result of later weathering or in special cases by replacement. The Jotnian sandstones represent a typical Molasse (Oldest Red), and that they may once have developed all these characteristics is shown by the famous Shoksha sandstone quarries in the Jotnian area west of the lake of Onega.

In Tables 2 and 3 some quantitative chemical data are compiled. They represent the Viborg area (Table 2) and the Hamra part (Table 3) of the Dalarne area which may be claimed as the best-known ones. From the chemical analyses the salic oxides, which are the chief mark of variability of the rapakivis, are recalculated relative to 100 per cent SiO_2 in order to facilitate their mutual comparability. The femic oxides remain nearly constant throughout the series, closely approximating to their proportions in the Jotnian sandstones and therefore, in the present discussion, which concerns the development of the rapakivis by replacement of the Jotnian sandstone, they are of minor importance in the evolution of the rocks and may be left without consideration (p. 368). The analyses are grouped together in conformity with the supposed stratigraphical position of the rocks (p. 360), i.e., in order of increasing CaO con-

TABLE 2

CHEMICAL ANALYSES OF ROCKS OF THE VIBORG AREA

	JOTNIAN SANDSTONES		RAPAKIVI GRANITES															
	1 T*	14 T	114 T	132 T	2 H	3 H	1 H	III W	4 H	21 H	IV W	9 H	5 H	6 H	7 H	8 H	10 H	12 H
CaO	0.25	0.37	2.18	1.65	1.30	1.41	1.93	1.65	2.72	2.94	2.98	3.08	3.97	4.34	3.76	5.53	4.01	4.29
Na_2O	0.12	0.09	3.10	1.57	2.96	3.50	3.72	2.99	3.91	3.87	4.17	4.13	4.90	4.38	5.38	4.34	4.48	4.20
K_2O	0.45	2.18	5.71	8.97	6.94	7.80	7.35	7.24	6.82	8.95	7.25	7.61	7.64	6.48	5.44	6.96	7.44	8.10
Al_2O_3	2.38	5.19	14.72	15.64	16.77	16.68	17.59	14.80	19.31	20.18	18.84	19.40	19.80	19.98	19.43	23.34	20.01	23.14
Total	3.20	8.83	25.71	27.83	28.98	29.39	30.59	26.68	32.76	35.94	33.34	34.32	36.31	35.18	34.46	40.17	35.94	39.73

* The numbering is that of the original investigators, the letters following the numbers giving the author's initials. *H*, Hackman; *W*, Wahl; *T*, Timofeev.

tent. As a basis of comparison in each case, analyses of Jotnian sandstones were chosen; these are placed on the left-hand side of each table. The stratigraphical position of these sandstones is not quite fixed (pp. 347, 360). In the Hamra subarea (Nos. 102 E and 103 E, Table 3) the sandstones represent a Middle Jotnian position, older than the porphyrites and the younger porphyries; in a chronological diagram von Eckermann[65] ascribes to them an early Jotnian age, although in the description he speaks of inter-Jotnian sedi-

TABLE 3

CHEMICAL ANALYSES OF ROCKS OF THE DALARNE (HAMRA) AREA

	JOTNIAN SANDSTONES		RAPAKIVI GRANITES						
	102 E *	103 E	92 E	93 E	94 E	95 E	96 E	97 E	98 E
CaO	0.25	0.24	0.47	0.80	0.89	1.41	2.58	2.81	2.61
Na_2O	0.24	0.26	4.50	4.66	4.38	5.80	5.87	5.60	6.21
K_2O	4.86	4.13	6.18	6.66	7.09	9.02	9.70	9.81	11.66
Al_2O_3	9.63	8.94	15.84	16.53	17.46	19.84	22.99	24.50	23.76
Total	13.98	13.57	26.99	28.65	29.82	36.07	41.14	42.72	54.24

* The numbering is that of the original investigator. The letter following it is the initial of the author, von Eckermann.

ments[66] which in the diagram referred to have a considerably higher stratigraphical position. For the Viborg area, where true Jotnian sediments have not yet been detected, the Svir sandstone area, between lakes Ladoga and Onega, has been used for comparison. Besides a couple of commercial (incomplete) analyses from the Shoksha sandstone quarries, there exist two complete ones: one of the (lower?) gray sandstone (14 T), the other of the (upper) red one (1 T). The stratigraphic position of these sandstones is not fixed, but on the shore of Lake Onega the red one (?) contains a granitic vein, from which it *could* be inferred that they do not belong to the uppermost Jotnian; this indication, however, may well be ambiguous. Otherwise chemical analyses of Jotnian sediments seem to be lacking.

[65] "The Loos-Hamra Region," *op. cit.*, p. 155.

[66] *Ibid.*, p. 299.

An inspection of the figures listed in Table 2 discloses the fact that on the whole the greater the sum of salic oxides coupled with one hundred SiO_2, the greater the amount of CaO present, allowing for some irregularities for rocks containing admixed and "transfused" dolerite material (Nos. 8 H to 12 H). Moreover, they show that between twenty and thirty parts by weight may have to be added to the original sandstone in order that the rapakivi composition may be attained. The addition of these salic oxides implies a volume increase within the rocks of a similar order of magnitude—an increase which, although conspicuously exceeding the measured porosity volume, as cited above (p. 384), may not have been far from that obtaining at the moment when replacement began. The statement made previously about the presence of CaO means that the potential porosity of the fresh sediments (with $CaCO_3$) may also have played a part in connection with this replacement. Moreover, on account of the wide distance between the stratigraphic equivalents from the Viborg area and the Svir sandstones, the intimations as to porosity can be only qualitative, and the supposed sandstone of the Viborg area may possibly have been widely different in respect to its total salic oxides. It must be added that the sandstone analyses used for comparison are those of selected pure quartzites; other partial analyses from the same Shoksha localities show other proportions of the feldspar minerals to be present.

In the Hamra subarea (Table 3), where the rocks considered are all in close local connection, the discussion approaches quantitative limits. The maxima and the minima to be added to the Middle Jotnian sandstone fluctuate within the limits of thirteen and twenty parts, of which the former figure, expressed in terms of volume, approaches an actual porosity even when the potentialities in this case are not taken into account.

The figures cited show that there seems to be no formal difficulty in transforming, without essential volume change, a Jotnian sandstone suite into a rapakivi granite by addition of material approximating in composition to sodium, potassium (and calcium?) aluminates. In a former memoir[67] the writer has considered and evalu-

[67] Backlund, "'Magmaaufstieg' in Faltengebirgen," *Bull. comm. géol. Finlande*, No. 115 (1936), pp. 293–347.

ated the field evidence relating to a transformation into a potassium-feldspar granite of a pure quartzite of Flysch facies occurring within the Gothokarelides at Västervik, southeast Sweden; this transformation was accompanied by increase of volume, the quartzites becoming rheomorphic, with excellently developed fluidal textures, and thereby partly dynamic. In the case considered above, the transformation seems to have been a static one, and therefore in its mechanics it perhaps approached what has been termed "metasomatism." This form of transformation, or granite genesis, is the only one which (seeing that the current modes of postulating the rapakivi form of body and emplacement, etc., have failed to introduce causal harmony between the various isolated field and laboratory observations) is able to resolve the apparent contradictions considered in foregoing pages of this paper, and to reduce them to a common denominator. The solution of the space problem—the most difficult one of the regional geology of deep-seated magmatic rocks, especially within the post-orogenic periods of orogenic regions—is here approached. As an example, only a single case, the structure (p. 343), may be further elucidated in connection with some observations referring to the unusual *moro* weathering (p. 358) of the rapakivi. On page 358 it was mentioned that the "indistinct, vaguely indicated bedding" of the granite rock conforms with the excellent horizontal jointing; this latter quality, together with the well-pronounced rectangular system of vertical joints, determines the unique quarrying properties of the rapakivi. The same is the case with the Jotnian sandstone (e.g., of Shoksha, with its famous quarrying possibilities). With the rapakivi originating as an equi-volume replacement, as pointed out above, its structural properties may have been inherited, with some modifications, from its sandstone stage of evolution. A second case of heritage may be the gray and red colors, which, respectively, characterize well-defined age variants of the rapakivis (e.g., Nystad), and which are by no means explicable by simple differentiation. The rocks in these cases may be derivatives from gray and red sandstones. In case of local marginal flow textures, the Archean gneisses of the surroundings may have been involved—with volume increment— in the granitization process.

b) Replacement accompanied by perceptible increment of volume.— As already pointed out in the section on "Association" (p. 347), the

rapakivis are locally associated with true extrusives of their own. If the genesis of these lavas be comparable with or similar to that described above, they may have abandoned their initial site of formation and have been forced to extrude at the earth's surface of that time, as a result of volume increment caused by an extra surplus influx of the supposed aluminates mentioned above and/or by an extra temperature rise. The first possibility is illustrated by Table 4, in which the analyses of the volcanic Dala porphyries, the surface equivalents of the rapakivis in the Hamra subarea, after having been

TABLE 4

COMPARISON OF THE CHEMICAL ANALYSES OF THE JOTNIAN SANDSTONES AND THE DALA PORPHYRIES OF THE DALARNE (HAMRA) AREA

	Jotnian Sandstones		Dala Porphyries								
	102 E*	103 E	74 E	76 E	77 E	78 E	81 E	75 E	79 E	83 E	82 E
CaO	0.25	0.24	0.51	1.11	1.30	1.36	2.05	2.14	2.58	3.93	3.98
Na_2O	0.24	0.26	2.62	5.19	4.84	4.84	5.67	3.79	5.83	6.53	8.06
K_2O	4.86	4.13	8.25	7.97	6.60	7.63	10.50	8.07	10.84	10.26	8.93
Al_2O_3	9.63	8.94	17.71	16.26	18.15	19.99	22.83	16.07	22.92	28.61	26.73
Total	13.98	13.57	29.09	30.53	30.89	33.82	41.05	30.07	42.17	49.33	47.70

* The numbering is that of the original investigator. The letter following it is the initial of the author, von Eckermann.

recalculated on the same basis as before (Tables 2 and 3), are compared with those of the same Middle Jotnian sandstones, which stratigraphically lie between an older and a younger porphyry sequence. The figures of the table show that throughout the whole series the quantity of salic oxides to be added to the sandstones is always somewhat higher in the case of the volcanic rocks, the lower and upper limits being fifteen and thirty-five parts, respectively, against thirteen and twenty in the case of the granites. It is true that the potential porosity in this case also seems to rise somewhat higher (see, e.g., the CaO contents in 82 and 83, Table 4), but, on the other hand, the real porosity percentage may initially have been lower; perhaps the appearance of corundum in the norm of some of these

extrusive rocks (74, 77, 78, Table 4), may be an indication that the initial sediments contained products of chemical weathering, such as clay components. If this were so, the volume increase may therefore have been so far greater as to promote the formation of rheomorphics (with conspicuous fluidal textures) which were extruded through the thin cover of sediments. The matter can also be expressed thus:[68]

$$\underbrace{\text{Emanations} + \text{sediments}}_{\text{granite}} + \text{emanations} = \underbrace{\text{extrusive rapakivi}}_{\text{magma}}$$

One cannot pass by the question of temperature rise because many parts of the extrusive rocks are reported as glassy or as having once been glassy, wholly or in part, with only a few relics and inclusions of the original sandstone minerals. The excellent microfluidal textures also may testify to magma genesis. Thus an extra volume increment may have arisen from thermal expansion, which would collaborate with the other sources of expansion in bringing about the extrusion of the rapakivi material. Only in this way can the close association of volcanics with abyssals of the same sequence be explained; otherwise the two facies should be separated by hundreds of meters of vertical distance, and even more in the horizontal plane, when reference may be made to the present surface.

With the solution of the rapakivi replacement, under conditions of constant volume as sketched above, the question of elements emigrating from the system as a consequence of the process scarcely arises. The more tangible, therefore, becomes the question of immigration. There are four principal elements or oxides to be accounted for: Al_2O_3, K_2O, Na_2O, and CaO. If calculated as aluminates, the molecular proportions of K_2O and Na_2O are nearly equal throughout, seldom rising to $K_2Al_2O_4 : Na_2Al_2O_4 = 2:1$, whereas $CaAl_2O_4$ fluctuates within wide limits. The proportion of this constituent to the sum of $(KNa)_2Al_2O_4$ ranges from zero to a quarter. These results indicate that CaO may not strictly belong to the dominant immigration elements but may have been wholly or partly fixed in the preexisting sediment. The composition of the latter at the time of deposition may have been gradually changing with respect to CaO, as comparison with later Molasse sediments shows.

[68] Holmes, *op. cit.*

Now the textural (p. 361), mineralogical (p. 363), and crystallization (p. 365) details all show that the remodeling of the sediment began with rising temperatures; the larger pre-existing quartz grains were attacked by the influx, while the smaller grains merely recrystallized, as also did occasional plagioclase grains and clusters of heavier mafic minerals. The first quartz-feldspar intergrowths were formed together with the first generation of rearranged allotriomorphic minerals. It may reasonably be supposed that, when the temperature rise was slow, the pre-existing microcline grains continued to grow as perthitic microcline; and when the temperature rose essentially faster, they were substituted by perthitic orthoclase. A new influx at nearly constant temperature, with perhaps a slight tendency to rise, may have induced the crystallization of the larger units; big phenocrysts were formed around pre-existing grains of potassium feldspar. But thermal conditions still fluctuating about the upper crystallization limits of the potassium feldspar may have inhibited the development of crystal faces, so that the incipient ones were promptly resorbed with formation of ovoids. The inclusion rings and margination textures may have come into being as incidental or final resorptions. Recrudescence of influx is perfectly illustrated by the rings of potassium feldspar around recrystallized matrix. The dominance of potassium feldspar crystallization and of quartz recrystallization during the first stages of rock transformation is conditioned by the chief sandstone components, quartz and microcline. A sudden fall in the temperature with an effectual decrease of influx of migratory material would provide conditions favorable to the development of a second generation of quartz-feldspar intergrowths. A sudden rise of temperature would favor the possibility of the crystallization of plagioclase and of the diffusion of CaO necessary for this purpose. The force of crystallization of the larger potassium feldspars would have already swept aside such lime-bearing material, and now, at this stage the plagioclase mantles would be formed, in part at the expense of a new influx, the homogeneous ovoids or clusters of mesostasis serving as centers and foci of crystallization. After their formation, with gradually falling temperature, the mesostasis between the ovoids would continue to be reorganized, and crystallization be brought to an end with a final development of fluorspar,

micropegmatite, and a certain amount of free quartz. The formation of idiomorphic femic minerals at the expense of pre-existing heavy mineral clusters would take place at the stage of pronounced rise of temperature, chiefly in connection with the growth of the plagioclase mantles; at this stage, or possibly independently a little later, fayalite also was formed. Throughout the whole course of recrystallization, concomitantly with the new developments, quartz and potassium feldspar grains were present in all stages of recrystallization and resorption as relics of the original sandstone. The mass as a whole was never liquid.

This sketch of the course of crystallization, the vestiges of which are found in the textural peculiarities, may be appropriate to the ovoidal rocks. In the other variants, even-grained and hypabyssal-porphyritic, it necessarily happens that only certain vestiges of the earlier evolution stages can be seen. The sudden rise of temperature may have been more marked, and the halting stages at constant temperature, with their possibilities for promoting localized crystallization, shorter. Fluctuations in temperature, instead of the steady fall which is commonly postulated, may in this case also have been important during the main stage of crystallization.

Finally, some attention may be given to the mode of migration by which the influxes (the calculated alkali aluminates) entered the sediments. This question touches upon the processes treated in the sections on "Weathering" (p. 357), "Chemistry" (p. 368), "Differentiation" (p. 372), and "Form of Rock Body" (p. 376), but not yet fully considered in the foregoing discussion. Some textural details constitute criteria of short periodic changes in the concentration of the crystallizing matter (inclusion rings, marginations, etc.). These are suggestive of diffusion processes, and in some ways they resemble the rhythmical progress of limestone granitization described by the writer elsewhere.[69] The direction of such a postulated diffusion may be governed (*a*) by the bedding planes of the sandstone and (*b*) by the isothermal planes. These two are parallel in an undisturbed sedimentary formation which has been superimposed on a perfect peneplain, and both combine to inhibit diffusion in the verti-

[69] "Der 'Magmaaufstieg' in Faltengebirgen." *op. cit.*

cal direction, whereas parallel to the bedding planes the diffusion tends to proceed more rapidly and to continue so long as the influx is active. Both combined may produce a sharp boundary of diffusion if the bedding, i.e., the contrast of grading, be pronounced or otherwise sharply marked. These conditions predispose the diffusion body to acquire a sheetlike form (p. 376). The diffusion capacity is governed by the porosity of the rock and also, perhaps, by the temperature. Some beds or occasional streaks within the diffusion body may be left unaltered, especially during the late declining phases of the diffusion, just as a wetted powder, when not sufficiently mixed, may contain unwetted patches (*moro*, p. 358). The diffusion process thus goes on within the limits of a bedded complex which, being of nearly equal grade, presents uniform facilities towards diffusion, the end product being a homogeneous granite of a certain chemical composition. The diffusion within the limits of bedded sandstone of another grade and of slightly different composition, especially where there is some difference in thermal and diffusion conditions, generates another granite, aberrant in texture and composition, but still falling within the broad limits of the range of chemical variation characteristic of magmatic rocks (p. 368). The form of body and the broad substantial variability of a Molasse sandstone complex is thereby reflected. The process has nothing to do with the magmatic differentiation of customary definition, the range of chemical composition being too narrow and the geological conditions too discordant for such a mode of genesis.

The problem of the sources of the influx or of the "emanation"[70] is the most difficult one, and as yet it is by no means ripe for discussion. The influx cannot have ascended as a regional mass migration from below—from beneath the granitic or sandstone bodies—because, as pointed out above (pp. 376, 379), the floor of these, where observed, remains completely unchanged. It must have passed upward, always as emanation, through well-defined and narrowly limited diffusion channels or pipes. It may also have been responsible for the temperature rise, thereby enabling its product, the granite, to present sharp limits both upward, against the roof, and down-

[70] Holmes, *op. cit.*

ward, against the floor. It cannot have arisen in connection with the deep-seated processes of basaltic intrusions and the associated "ossipitic" transformations because, as shown above, the "emanation" developed on that occasion was of a completely different composition. It may be that erosion remnants of such diffusion channels, well defined morphologically, still remain unrecognized (with the exception of Sederholm's indication) within exposures of the older rocks. Perhaps the influx may be a superficial post-orogenic manifestation of rearrangements within the lower parts of the earth's crust consequent upon the immediately preceding orogeny. The occurrence within the labile zones of the Molasse areas would in this case be readily comprehensible. Thus the rapakivis and the dolerites share in common the tectonic milieu of their location and the sedimentary formation of their emplacement. The latter is one of the factors governing the "smooth differentiation curves." Otherwise the two magmatics are genetically quite different.

RADIOACTIVITY

The rapakivis are among the most strongly radioactive of granitic rocks.[71] Genetic considerations suggest that this peculiarity may not be accidental. The turbulent accumulation of debris of older crystalline rocks, followed by that of the detritus of its own subsequent and repeated decomposition, may have promoted a successive enrichment of radioactive substances. The latter are particularly associated with the heavy minerals, which themselves may be concentrated by the turbulent accumulation of the sediments. The serial granitizations of the sediments described above resulted in a reassembling of the material, including the heavy minerals, as large crystals, and so in the case of subsequent weathering of the granite, the recrystallized radioactive minerals are protected from a final and large dispersion. The extreme radioactivity thus fits well into the history of development of the rapakivi rocks.

CONCLUSION

The idea of the development of granitic bodies out of quartzitic or sandstone sediments is not a casual or a new one. Among other

[71] Holmes, "Radioactivity and Geological Time," *Nat. Res. Council Bull.* 30 (1931), p. 275.

examples, reference may be made to the direct field evidences of an analogous development, from a Flysch quartzite in southeastern Sweden, a granite with such similar chemical and mineralogical properties[72] that more than once it has been confused with the true rapakivi granite. It was this example that led the writer to re-examine and discuss all the known evidence relating to the rapakivi granites, since the field evidences of the latter were far from being so clear as in the case of southeastern Sweden. The case was also considered in a series of lectures on vulcanism held at this university. It was then realized that our present time is broadly comparable with former Molasse phases of geological history as regards the vulcanicity, as well as the denudation, sedimentation, and tectonic processes. As to the Jotnian in Fennoscandia, with its granites and dolerites, it represents a late pre-Cambrian Molasse, and, therefore, geological comparisons of all parts were made, on the basis of broad field experiences, with the modern and past vulcanism of Iceland, with the Tertiary vulcanism of East Greenland, and with the Quarternary vulcanism of Patagonia. The analogies, apart from local peculiarities such as those due to differences in depth of exposure, were surprising. With respect to the contrasting acid and basic rocks and their mutual relations the similarities were nearly complete.

As to the rapakivi granite, which hitherto has always been considered as the most typical, yet unique, "magmatic" rock within the pre-Cambrian of Fennoscandia, the conclusions reached as a result of this discussion may seem strange and surprising. Yet the mode of genesis described above is the only one which reconciles all the puzzling and apparently contradictory observations. Johannsen's recognition of the rapakivis as "abnormal granites" may register a subtle diagnosis, the abnormality referring not so much to the idea that granitization of post-tectonic, nearly undisturbed sediments, is an exceptional geological process, but rather to the conclusion here reached that the granitization was achieved without any noteworthy change of volume. In another memoir[73] on the geotectonics of Fennoscandia the writer has treated the rapakivi granites as re-

[72] Backlund, "Der 'Magmaaufstieg' in Faltengebirgen," *op. cit.*

[73] "Die Umgrenzung der Svekofenniden," *loc. cit.*

placements of the Gothokarelian Molasse, but without presenting convincing evidences. The foregoing discussion may fill this gap. Moreover, De Lapparent[74] has tentatively proposed a similar solution but without reference to the geotectonics. The present investigation may serve as an amplification of the idea from many points of view.

ACKNOWLEDGMENTS.—My sincere thanks are due to Professor A. Holmes and Dr. Doris L. Reynolds of Durham for reading the typescript and correcting the style, and for various indications of their own findings in similar fields of investigation.

August 12, 1937

[74] J. de Lapparent, "Courses géologiques en Finlande," *Soc. Géol. France Bull.*, Vol. II (5th ser., 1932), pp. 145–75.

CRYSTALLIZATION EQUILIBRIUM IN NEPHELINE-ALBITE-SILICA MIXTURES WITH FAYALITE

NORMAN L. BOWEN AND J. F. SCHAIRER
Geophysical Laboratory, Carnegie Institution of Washington

ABSTRACT

This paper presents the results of a thermal study of the system, $NaAlSiO_4$-FeO-SiO_2, and discusses their application to petrology. The crystalline phases formed in the various compositions are cristobalite, tridymite, albite, fayalite, nepheline, carnegieite, hercynite, and wüstite. There are two ternary eutectics, one between tridymite, albite, and fayalite (temperature 980° ± 10° C.), which may be regarded as a simplified fayalite rhyolite, and the other between nepheline, albite, and fayalite (temperature 990° ± 10° C.), which may be regarded as a simplified fayalite phonolite. These and other findings are discussed in connection with the origin of natural phonolites, trachytes, and rhyolites carrying fayalite.

INTRODUCTION

With the progress of equilibrium studies of the alkali-alumina silicates and of iron silicates it has become desirable to proceed to an examination of equilibrium in mixtures containing both of these. A beginning has been made with the system, $NaAlSiO_4$-FeO-SiO_2. Apart from the intrinsic interest of such compositions, a principal reason for their study is the practical one that the iron silicates give liquids of low viscosity in which crystals form readily at appropriate temperatures, and their addition to alkali-alumina silicates endows the complex mixtures in some measure with these desirable attributes, attributes conspicuously lacking in the alkali-alumina silicates themselves. Moreover, this fluxing effect of the iron silicates not only permits the direct determination of equilibrium relations in the complex mixtures but, by a short extrapolation, may enable the indirect determination of these relations in the alkali-alumina silicates in compositions for which, on account of their sluggish behavior, direct determinations are impossible or so indecisive as to require independent confirmation.

These considerations are well illustrated by the initial work upon the system, for which were chosen mixtures of albite and fayalite, two compounds whose relation to the system as a whole may be seen in Figure 1. Although albite ordinarily crystallizes with great re-

luctance in alkali-alumina silicate mixtures, nevertheless in liquids of the albite-fayalite system crystallization of albite occurs readily, and it was possible to obtain equilibrium between liquid and crystals with consequent solving of all the relations of the system. The results of this initial work have been published elsewhere[1] and the equilibrium diagram is here reproduced as Figure 1. Examination of this diagram shows that independent confirmation is furnished of the determination of the melting-point of albite at 1122° ± 4°,

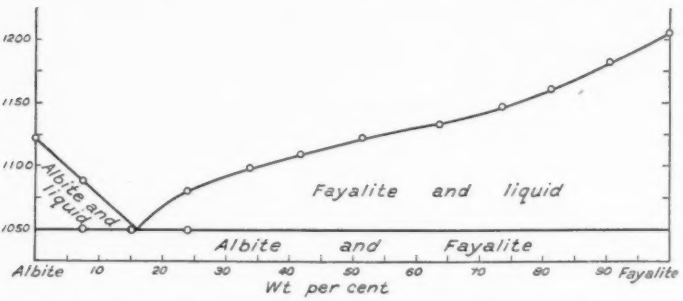


FIG. 1.—Equilibrium diagram of the system, albite-fayalite

since this value agrees with other liquidus determinations in the system.

The extension of these studies to the general system now concerns us.

FUNDAMENTAL SYSTEMS

Of the three fundamental systems represented by the side lines of Figure 2, two have already been investigated. The results for the system FeO-SiO_2 have been published elsewhere.[2] The system, $NaAlSiO_4$-SiO_2, with its compound, $NaAlSi_3O_8$ (albite), has been investigated, the $NaAlSiO_4$-$NaAlSi_3O_8$ portion by Greig and the $NaAlSi_3O_8$-SiO_2 portion by Schairer. The results will be published shortly. The third fundamental system, $NaAlSiO_4$-FeO, has not been investigated because it is, on the whole, without petrologic

[1] N. L. Bowen and J. F. Schairer, *Proc. Nat. Acad. Sci.*, Vol. XXII (1936), pp. 345–50.

[2] Bowen and Schairer, "The System, FeO-SiO_2," *Amer. Jour. Sci.*, Vol. XXIV (1932), pp. 177–213.

importance. Indeed, our mixtures have been extended in the iron-rich direction only as far as the nepheline-fayalite join, where already two complications begin to appear: one of them, the extension of the field of wüstite across that join, which is not of serious consequence, since all compositions can still be represented in terms of the same components; and the other, the coming-in of the field of hercynite (see Fig. 2), whereupon the possibility of representation in terms of three components ceases. The purpose in using a diagram with FeO as one of the components is that it greatly facilitates the plotting of the composition of individual mixtures, the method of their preparation being such that the amount of FeO in the final product differs from the amount calculated from the original mixture for reasons to be explained, and the point representing the composition of the final product being obtained by a simple construction also to be discussed.

METHODS

PREPARATION OF MIXTURES

Mixtures for use in thermal investigation were made by taking SiO_2, Fe_2O_3, Al_2O_3 and carefully prepared $Na_2O \cdot 2SiO_2$ in calculated proportions and melting them together in a platinum crucible in a Meker furnace, a procedure repeated three times with intermediate grinding. Under these conditions some of the iron of the charge is taken up by the platinum crucible, and some of the iron oxide remaining in the charge persists in the ferric state. We then melted the product in a crucible of pure electrolytic iron in an atmosphere of nitrogen, again repeating three times. During this treatment most of the ferric oxide reacts with the iron of the crucible to give ferrous oxide, and there is thus an addition of iron to the charge which is compensatory to the previous loss of iron to the platinum crucible. The state of balance between these two effects cannot be predicted. The amount of iron in the final product is determined only by analysis. In mixtures of the present system the net effect is always an enrichment of the product in iron. For the purpose of solving general relations in the system this aberrancy of the composition of the product makes no difference because the relative proportions of all the other ingredients remain the same whatever vicissitudes the iron content

experiences, and the composition of the final product must lie upon a line passing through the composition calculated from the initial ingredients and the FeO apex of the triangle. In order to plot the final composition, it is only necessary to determine the iron content and to place a point on that line at the determined value of total Fe expressed as FeO. Upon this last phrase some comment is perhaps desirable, although it has been discussed fully in an earlier paper. Iron-bearing silicate melts in equilibrium with metallic iron always contain a small proportion of their iron in the ferric state. In virtue of the presence of this ferric iron in the liquids, the system is not truly ternary, but the degree of departure is very small and the presentation of the results is greatly facilitated by calculating all the iron as FeO and plotting it accordingly, a procedure which has been adopted in plotting all the points in Figure 2. The actual amount of Fe_2O_3 in each liquid at its liquidus temperature is given in Table 1.

METHODS OF CHEMICAL ANALYSIS

Ferrous oxide was determined by the Pratt method modified somewhat, as described in detail in a former paper.[3] Total iron was determined by dissolving 0.2–0.4 gram sample in 15 cc. (1 : 1 by volume) H_2SO_4 and 10 cc. of 40 per cent hydrofluoric acid in a large platinum dish and heating until all HF had disappeared. The dish was cooled, contents diluted, the iron reduced by means of a Jones reductor,[4] and the total iron titrated with $KMnO_4$ solution. Blanks were run on the Jones reductor to prove the absence of Fe in the zinc amalgam used. The difference between total iron and FeO gave the Fe_2O_3 present. The amounts of Na_2O, Al_2O_3, and SiO_2 are, of course, fixed by synthesis and require no analytical determination.

METHODS OF THERMAL INVESTIGATION

The heat treatments whereby equilibrium between crystalline silicates and liquid was determined were carried out in a platinum-wound resistance furnace through which a stream of nitrogen was passed. The nitrogen had had its oxygen content reduced to a very

[3] N. L. Bowen, J. F. Schairer, and E. Posnjak, "The System, CaO-FeO-SiO_2," *Amer. Jour. Sci.*, Vol. XXVI (1933), p. 197.

[4] F. P. Treadwell and W. T. Hall, *Analytical Chemistry*, Vol. II: *Quantitative Analysis* (7th ed.; New York, 1930), p. 539.

TABLE 1

EQUILIBRIUM DETERMINATIONS

Composition of Liquid at Liquidus Temperature				Temperature of Completion of Melting ± 5° C.	Refractive Index of Glass ± .003
$NaAlSiO_4$	SiO_2	FeO	Fe_2O_3		
Mixture Having Cristobalite as Primary Phase					
10.6	66.5	23.12	0.32	1,475	.....
Mixtures Having Tridymite as Primary Phase					
32.3	61.8	4.98	0.91	1,055	1.490
25.7	67.3	6.56	0.41	1,245	1.495
19.5	68.3	12.08	0.13	1,315	1.507
19.7	59.4	20.58	0.34	1,258	1.544
14.8	63.8	21.24	0.22	1,390	1.543
19.8	54.1	25.82	0.31	1,182	1.567
15.0	49.8	34.89	0.33	1,218	1.61
9.3	46.5	43.72	0.44	1,281	1.65
4.5	49.0	45.84	0.62	1,445	1.68
9.3	41.4	48.63	0.65	1,150	1.69
Mixtures Having Fayalite as Primary Phase*					
35.7	58.7	5.50	0.11	1,012	1.495
59.5	29.6	10.70	0.17	1,009	1.529
52.5	36.0	11.10	0.35	1,050	1.530
34.0	53.6	11.98	0.45	1,063	1.521
46.0	41.9	11.82	0.33	1,056	.....
48.4	39.0	11.88	0.78	1,042	1.530
29.0	58.0	12.82	0.22	1,084	1.520
43.1	43.2	12.98	0.73	1,060	.....
34.9	49.5	14.97	0.69	1,078	1.535
58.3	24.2	16.83	0.67	1,038	1.555
41.8	41.0	16.60	0.60	1,077	.....
49.5	29.9	20.02	0.59	1,066	1.563
41.4	37.4	20.58	0.63	1,084	1.562
24.2	53.2	22.36	0.21	1,114	1.553
28.8	48.1	22.65	0.47	1,105	1.561
57.3	19.1	22.58	1.02	1,105	1.584
34.1	41.9	23.68	0.37	1,100	1.566
36.5	39.4	23.40	0.74	1,097	.....
49.7	24.7	24.86	0.75	1,074	1.587
45.0	22.1	30.63	2.25	1,087	1.620
38.0	28.5	31.96	1.50	1,099	1.618
18.7	46.8	33.59	0.95	1,123	1.606
31.1	34.1	33.77	1.01	1,111	1.617
39.8	24.9	32.98	2.35	1,092	1.633
19.7	39.4	40.06	0.81	1,126	1.637
29.3	29.3	39.56	1.83	1,122	1.642

* Additional points in the albite-fayalite system already published.

TABLE 1—*Continued*

Composition of Liquid at Liquidus Temperature				Temperature of Completion of Melting ± 5° C.	Refractive Index of Glass ± .003
$NaAlSiO_4$	SiO_2	FeO	Fe_2O_3		
Mixtures Having Fayalite as Primary Phase*—*Continued*					
20.0	33.7	44.58	1.72	1,134	.....
29.1	24.0	45.07	1.81	1,106	1.695
9.3	41.4	48.63	0.65	1,150	1.690
19.1	28.6	50.96	1.33	1,142	1.72
9.4	37.5	52.36	0.68	1,155	1.71
14.7	31.2	52.33	1.77	1,152	.....
10.1	31.1	57.41	1.44	1,167	.....
Mixtures Having Albite as Primary Phase*					
35.7	58.7	5.50	0.11	1,012	1.495
59.5	34.6	5.66	0.22	1,050	1.512
40.2	52.0	7.40	0.40	1,050	1.508
52.5	36.0	11.10	0.35	1,037	1.530
Mixtures Having Nepheline as Primary Phase					
62.0	29.4	8.21	0.34	1,020	1.523
69.1	19.8	10.84	0.22	1,140	1.54
75.9	12.7	10.95	0.41	1,259	1.54
63.7	24.6	11.40	0.34	1,045	1.54
64.3	19.7	15.54	0.42	1,120	1.554
72.3	9.6	17.37	0.70	1,255	1.564
57.3	19.1	22.58	1.02	1,105	1.584
Mixture Having Carnegieite as Primary Phase					
77.5	9.7	12.40	0.45	1,293	.....
Mixtures Having Hercynite as Primary Phase					
57.3	19.1	22.58	1.02	1,105	1.584
67.0	8.5	23.36	1.12	1,245	.....
46.7	18.6	32.45	2.22	.....	1.627
38.8	20.3	37.80	2.89	.....	1.66
Mixture Having Wüstite as Primary Phase					
29.1	24.0	45.07	1.81	1,106	1.695

low value by passing it through a tube packed with steel wool heated to 650° C. This means of purifying commercial nitrogen has been found more convenient than that involving the use of the ammoniacal cuprous chloride tower, which we formerly used, and is at the same time entirely satisfactory for our purpose. In this stream of nitrogen the charge was supended in an iron crucible, and equilibrium was determined by the method of quenching combined with microscopic examination to determine the nature of the phases present, methods that have been adequately described in previous publications. It may be pointed out that control by means of microscopic examination is constantly practiced in this work. Thus, determination of the refractive index of the glasses is always made, and the index of the glass obtained when the liquidus temperature is determined must correspond with that of the larger quantity of material prepared for chemical analysis from the same mixture. The refractive indices of all such glasses are given in Table 1. The figures are only approximate because we were not interested in absolute values but only in comparing indices of different runs of the same material in order to insure an identical end product. They may, nevertheless, be of some service in other work and are given for that reason.

In the calibration of the quenching apparatus, standard melting-points were used, defined as follows: NaCl 800°.4, Au 1062°.6, Li_2SiO_3 1201°, $CaMgSi_2O_6$ 1391°.5, and Pd 1549°.5 C.

RESULTS OF QUENCHING EXPERIMENTS

The results of equilibrium determinations by the method of quenching are given in Table 1, upon which no comments are necessary except the statement that the time required for equilibrium varies from 20 minutes in iron-rich mixtures to about 48 hours in mixtures with only 5 per cent iron oxides.

EQUILIBRIUM DIAGRAM

With the aid of the determinations detailed in Table 1, the equilibrium diagram of the ternary[5] system has been constructed and is given as Figure 2.

[5] Ternary only when the small amounts of Fe_2O_3 in the liquids are neglected. Hereafter we shall use the designation "ternary" without referring to this qualification, which is to be understood.

THE VARIOUS FIELDS

In the determined part of the diagram much the largest field is that of fayalite. This is a rather unexpected condition in view of the fact that fayalite has such a comparatively low melting-point. Nevertheless, it is a fact that the field of fayalite extends over to

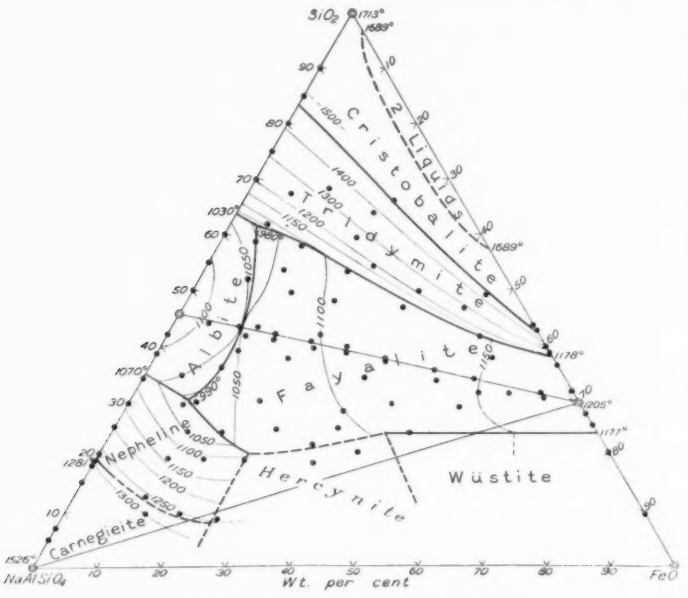


FIG. 2.—Equilibrium diagram of the system, $NaAlSiO_4$–FeO–SiO_2. A revision of the preliminary diagram published in *Amer. Jour. Sci.*, Vol. XXXIII (1937), p. 9.

compositions very rich in the alkali-alumina silicates. The field of albite is, on the other hand, quite small, and the two ternary eutectics—that between albite, fayalite, and tridymite and that between albite, fayalite, and nepheline—are not far from the alkali-alumina silicate side of the triangle.

The field of carnegieite is separated from that of nepheline by a boundary curve which has a temperature of 1281° C. in the compositions free from iron, a determination made by Greig, and goes to somewhat lower temperatures in the ternary system.

The field of hercynite, $FeO \cdot Al_2O_3$, has not been sharply delimited, but a considerable portion of the nepheline-fayalite join lies in that field. The coming-in of this phase gives equilibria that cannot be completely described in terms of three components, and investigation of mixtures in that region was not further pursued.

The field of wüstite requires no special comment except that it, too, extends across the nepheline-fayalite join. For these compositions the equilibrium remains ternary, if the Fe_2O_3 content is neglected, a procedure adopted for all mixtures in other parts of the diagram. In these iron-rich mixtures, however, the Fe_2O_3 content mounts to such values that this procedure can no longer be followed safely, and no extensive study was therefore made of mixtures in the wüstite field.

The boundary between the fields of cristobalite and tridymite is simply the isotherm of 1470° C., the temperature of inversion. It should be pointed out that in mixtures of this system tridymite was not formed during the equilibrium runs except when special precautions were taken, and the equilibria determined in the field where tridymite should be the stable phase were usually cristobalite equilibria. The departure of the liquidus surface of tridymite from the metastable surface for cristobalite would undoubtedly be very small, and the determinations may be taken as adequately representing the values for the stable equilibrium, tridymite-liquid.

The field of two liquids has not been delimited because it lies at temperatures above the melting-point of iron, beyond which temperature work with iron crucibles cannot, of course, be extended. The boundary of this field is merely sketched in to indicate the existence of such a field and the general shape which it must assume.

SUBSYSTEMS

The binary system, albite-fayalite, is the only portion of the general system that can be treated as a separate system. It has been described in a paper already referred to, and the diagram is here given as Figure 1.

The join, nepheline-fayalite, cannot, for reasons already given, be treated as binary, nor does a section along that join serve any significant purpose.

Since there are no ternary compounds, there are no ternary subsystems other than the albite-fayalite-silica system.

COURSES OF CRYSTALLIZATION

The crystallization of the great majority of compositions is too simple to require detailed comment. It is of the eutectic type, and nearly all mixtures proceed in a simple manner to one or the other of the two ternary eutectics, depending upon the original composition. The position of these eutectics at high content of alkali-alumina silicates and relatively low content of iron may, however, be especially emphasized. As a result, the late-crystallizing material of any mixture will ordinarily be rich in alkali-alumina silicates.

For those mixtures on the nepheline-fayalite join which lie in the hercynite or wüstite fields certain complications may be noted. From them either hercynite or wüstite will be the first crystals to separate, but at a later stage these oxide phases will, with perfect equilibrium, react with liquid to form silicate phases, the wüstite forming fayalite and the hercynite forming both fayalite and nepheline. The details of these reactions are not fixed by any of the relations determined in the ternary system. If, for any reason, there is failure of reaction of crystals with liquid, serious complication results because the liquid moves to compositions not representable in the plane of the triangle and can never be brought back into that plane. This is, of course, because the composition of hercynite does not lie in the plane of the triangle. It might appear, therefore, that the behavior last described would obtain only with those mixtures lying in the hercynite field, but, in point of fact, for all mixtures in the wüstite field and on the nepheline-fayalite join, hercynite is the second phase to crystallize. Moreover, even from those mixtures of fayalite and nepheline which lie in the fayalite, nepheline, or carnegieite fields hercynite separates at some stage of crystallization so that departure from the plane of the triangle is common to all of them.

This separation of an oxide phase in excess of its stoichiometric proportion will, when accompanied by failure of resorption, necessarily result in enrichment of residual liquids in silica, an almost universal relation in silicate melts. We may refer in particular, in

this connection, to the similar relation of another iron-oxide phase, namely, ferric oxide itself (hematite) in certain alkalic mixtures.[6]

PROPERTIES OF THE CRYSTALLINE PHASES

For the most part the crystalline phases require no special comment. *Cristobalite* shows the characteristic octahedral form and very low refractive index. *Fayalite* forms equant crystals in most mixtures, but in the more viscous mixtures, rich in albite and silica, it is characteristically in thin plates tabular // 100, just as in the lithophysae of rhyolites. The refractive indices are $\gamma = 1.875$, $\beta = 1.864$, $\alpha = 1.824$. *Albite* gives crystals tabular // 010, showing polysynthetic twinning with the lamellae so thin as to render measured values of the optical properties uncertain. The maximum extinction in the symmetrical zone is about 18°, and the refractive index γ is very close to 1.535. *Nepheline* appears in the characteristic form of stout prism with base. *Hercynite* forms sharp octahedra of refractive index $1.83 \pm .01$. *Carnegieite* is in the usual rounded grains with complicated twinning analogous to that of leucite and formed in the same manner by inversion from an isotropic form.[7]

PETROLOGIC CONSIDERATIONS

In an earlier paper, of somewhat popular character, attention was called to the ascertained facts that in the plagioclase series fractional crystallization will bring about enrichment of the liquid in albite, and in the olivine series it will induce enrichment of the liquid in the iron olivine, fayalite; and then the following questions were asked: "What will the net result be if these two effects occur in a single liquid of complex composition? We cannot get a residual liquid that has 100 per cent alkali feldspar and also 100 per cent iron silicate. What balance is struck between these effects?"[8] The answers were not then forthcoming but, in the light of the present results, can now be stated with much confidence. Because both ter-

[6] N. L. Bowen, J. F. Schairer, and H. W. V. Willems, "The Ternary System: Na_2SiO_3-Fe_2O_3-SiO_2," *Amer. Jour. Sci.*, Vol. XX (1930), pp. 444–45.

[7] N. L. Bowen and J. W. Greig, "The Crystalline Modifications of $NaAlSiO_4$," *Amer. Jour. Sci.*, Vol. X (1925), pp. 204–12.

[8] Norman L. Bowen, "The Igneous Rocks in the Light of High-Temperature Research," *Scientific Monthly*, Vol. XL (1935), p. 502.

nary eutectics and also the binary eutectic albite-fayalite all lie at high concentrations of alkali-alumina silicates and comparatively low concentration of iron silicate, we can say that the net result of fractional crystallization in the complex liquid will be enrichment in alkali-alumina silicate. Absolute enrichment in iron silicate does not occur but rather only enrichment in iron silicate relative to magnesian silicate.

Therefore, when we find evidence of such relations between rock types in nature, we may with considerable confidence regard these relations as the results of fractional crystallization. Igneous rocks which contain an olivine approaching Fe_2SiO_4 in composition do not bulk large in nature, but they are nevertheless widespread. They are always rich in alkali-alumina silicate, that is, in alkali feldspars alone or together with quartz or nepheline and thus belong among the trachytes, rhyolites, and phonolites. No other types of igneous rocks contain the fayalite member of the olivine series, a most suggestive fact. The mineral association is exactly that to be expected if these rocks were late products of fractional crystallization. More than that, the rock association ordinarily confirms this relation, for the alkali basalts, trachyandesites, and other types occurring with these salic-alkalic types bear internal evidence that the course of crystallization is toward a more salic and alkalic liquid in which iron is emphasized at the expense of magnesia.

Among effusive igneous rocks, fayalite-bearing types are widely represented. They are, as noted, always alkali-rich, and soda is almost invariably the dominant alkali. Highly sodic rocks are frequently associated with tensional faulting and foundering of the earth's crust. It cannot be maintained that sodic rocks are confined to regions displaying that type of orogeny, and the concept has certainly been overemphasized in that classification of rock types which divides them into Atlantic and Pacific branches on the basis of supposed orogenic control. Nevertheless, it cannot be denied that sodic rocks do seem to be emphasized in regions of foundering, and there, in the appropriate types, fayalite is frequently found.

From islands of the Mediterranean, notably Pantelleria, fayalite-bearing trachytes and rhyolites have been described by Soellner[9]

[9] J. Soellner, *Zeit. Kryst.*, Vol. XLIX (1911), p. 144.

and by Washington.[10] From Iceland, Hawkes has described a highly siliceous dacite, rich in soda and bearing fayalite.[11] Volcanic islands standing upon the mid-Atlantic ridge, such as Ascension and Gough Islands, show fayalite-bearing trachytes and rhyolites.[12]

In the Pacific, the Galapagos Islands and Easter Island stand upon a ridge that appears to link the Antillean region with Antarctica. On Easter Island there occurs fayalite-bearing obsidian, rich in alkalis and particularly in Na_2O.[13] Thus, in mid-Pacific we have rocks that belong to the "Atlantic" suite and are at the same time highly siliceous, though the possibility of the occurrence of rocks rich in silica in the Pacific basin has been questioned.

Among the rocks of the volcanic girdle of the Japan Sea, fayalite-bearing trachytes are well represented.[14]

In the region of the Great Rift Valley of Africa, the lavas are characteristically soda-rich, and in the leucocratic varieties fayalite is sometimes present. Smith has found it in phonolite,[15] and Bowen describes very rare phenocrysts in a rhyolitic obsidian.[16]

In all these rocks we are, of course, dealing with much more complex mixtures than those of the investigated system, but the principal additional component is orthoclase, and it undoubtedly behaves in the same general manner as albite.[17] We are concerned also with other iron-bearing phases in addition to fayalite, and much of the iron may occur in soda-iron amphiboles and pyroxenes, but even these afford evidence of enrichment of iron relative to magnesia in these low-melting residua.

In Table 2 are given the analyses of three typical fayalite-bearing lavas, a rhyolite, a trachyte, and a phonolite, and with them, for

[10] H. S. Washington, *Jour. Geol.*, Vol. XXI (1913), p. 705.

[11] L. Hawkes, *Quart. Jour. Geol. Soc. London*, Vol. LXXX (1924), pp. 549–67.

[12] R. Reinisch, *Deutsche Südpolar-Expedition*, Vol. II (1912), p. 647; W. Campbell Smith, *Report on the Geological Collections Made during the Voyage of the "Quest," 1921–22* (British Museum [Natural History] 1930), p. 93.

[13] A. Lacroix, *Comptes rendus*, Vol. CCII (1936), pp. 529 and 603.

[14] T. Tomita, *Jour. Shanghai Science Inst.*, Vol. I (1935), pp. 254–56.

[15] W. Campbell Smith, *Quart. Jour. Geol. Soc. London*, Vol. LXXXVII (1931), pp. 249–50.

[16] N. L. Bowen, *Amer. Jour. Sci.*, Vol. XXX (1935), p. 482.

[17] N. L. Bowen, *Amer. Jour. Sci.*, Vol. XXXIII (1937), pp. 7–8.

comparison, the compositions of three eutectics in the investigated system. The relationships are striking and tend to confirm the character of the natural lavas as residuals of fractional crystallization.

TABLE 2

CHEMICAL COMPOSITIONS OF FAYALITE-BEARING ROCKS AND SYNTHETIC MIXTURES

	I	II	III	IV	V	VI
SiO_2	75.55	76.4	63.30	62.5	57.05	55.8
Al_2O_3	12.31	12.2	16.38	16.9	19.73	21.9
Fe_2O_3	0.69	.....	2.54	.....	1.85	.....
FeO	1.17	4.0	2.36	11.0	4.31	9.0
MgO	0.04	.....	0.84	.....	0.34	.....
CaO	0.23	.....	1.62	.....	1.56	.....
Na_2O	4.55	7.4	6.36	9.5	7.54	13.3
K_2O	4.69	.....	4.41	.....	4.85	.....
H_2O+	0.15	.....	0.83	.....	0.54	.....
H_2O-	none	.....	0.10	.....	0.68	.....
TiO_2	0.13	.....	0.71	.....	0.82	.....
P_2O_5	0.01	.....	0.30	.....	0.23	.....
Cl	0.21	.....	.....	.....	.....	.....
F	0.28	.....	.....	.....	.....	.....
MnO	0.04	.....	.....	.....	0.35	.....
S	0.01	.....	.....	.....	.....	.....
Total	100.06	100.0	99.75	100.0	99.85	100.0
	−0.16	.....	.....	.....	.....	.....
	99.90	.....	.....	.....	.....	.....

I. Rhyolite obsidian, fayalite-bearing, Lake Naivasha. A. Willman, anal., in N. L. Bowen, *Amer. Jour. Sci.*, Vol. XXXIII (1937), p. 14.

II. Simple synthetic "soda rhyolite," being ternary eutectic of albite, fayalite, and tridymite.

III. Trachyte, fayalite-bearing, Pantelleria. H. S. Washington, anal., H. S. Washington, *Jour. Geol.*, Vol. XXI (1913), p. 688.

IV. Simple synthetic "soda trachyte," being binary eutectic of albite and fayalite.

V. Phonolite, fayalite-bearing, Nyeri Hill, Kenya. W. H. Herdsman, anal., in W. Campbell Smith, *Quart. Jour. Geol. Soc. London*, Vol. LXXXVII (1931), p. 249.

VI. Simple synthetic "soda phonolite," being ternary eutectic of albite, nepheline, and fayalite.

There are, of course, outstanding differences between the natural lavas and their synthetic relatives, the principal one being the much greater quantities of FeO in the latter. Possible explanation of this lies in the fact that in the natural lavas the alkali content is only partly Na_2O; much of it is K_2O, and iron compounds are probably

less soluble in potash-rich liquids than in soda-rich. Moreover, a considerable proportion of the iron of the lavas is ferric, and this leads to a lessening of the solubility of iron oxides unless there is an excess of alkalis over alumina, which is still another problem. These suggestions are, however, only suggestions. They await the test of further investigation.

Among deep-seated igneous rocks, fayalite-bearing types do not appear to be so common as among effusive rocks. Perhaps the most conspicuous occurrence is an intrusive complex of alkalic rocks of central Wisconsin, in which are represented certain basic types together with sodalite and nepheline syenites, quartz syenite, and granite. Fayalite has been found in the three last-mentioned types and thus has the same range of occurrence as in their effusive equivalents in the Great Rift Valley region. Amphiboles rich in iron are well represented in the Wisconsin types also.[18]

In summary, then, it may be stated that the rock types discussed, both deep-seated and effusive, show that kind of joint enrichment in alkaluminous silicates and iron silicates which experiment leads us to expect in residual liquids, and therefore we may consider the composition of the rocks as indicative that fractional crystallization was the dominant control in their development

[18] S. Weidman, *Wisconsin Survey Bull. 16* (1907), pp. 177–354.

A CONTRIBUTION TO THE KNOWLEDGE OF THE LATE SODIC DIFFERENTIATES OF BASIC ERUPTIVES

HARRY VON ECKERMANN
Sparreholm, Sweden

Sodic rest-magmas, occurring as veins and dikes within basic rocks of doleritic composition, are a fairly common feature. Undoubtedly they are in most cases exponents of the late differential action within the cooling mother-magma and may, consequently, be used to gain additional knowledge of the laws governing the closing stages of magmatic activity.

Few analyses of such rocks are published, however, and most of them lack the necessary addendum of the actual mineral composition. Even if the quantitative importance of the sodic rest-magmas may be small, their theoretical interest justifies a closer study than that hitherto given them.

While investigating the great Swedish Jotnian area of Dalecarlia, part of which has been described in the memoir of the Loos-Hamra region,[1] the present author was struck by the absence of any such dikes within the enormous sheets of diabase of doleritic composition covering, or intruded into, the Jotnian sediments. But, on comparing the results obtained within the Dalecarlian area with those from the corresponding Jotnian region of Nordingrå and Rödö islands on the Swedish east coast,[2] he was equally impressed by the numerous late-differentiate dikes observed within the diabases and gabbros at the latter locality.

Details of some of these dikes have already been published by previous investigators. On a small island named Gubben, outside Rödö, P. J. Holmquist in 1899[3] found and described narrow sodic

[1] Harry von Eckermann, "The Loos-Hamra Region," *Geol. Fören. Förh.*, Vol. LVIII (1936).

[2] "The Jotnian Formation and the Sub-Jotnian Unconformity," *ibid.*, Vol. LIX (1937).

[3] "Rödöområdets rapakivi och Gångbergarter," *Sveriges Geol. Undersökning*, Ser. C (1899).

dikes (1–2 cm. wide), intersecting doleritic diabase, which he named "albite-pegmatites." Their mineral composition was found to be:

	Per Cent		Per Cent
Albite	55.6	Ores	2.3
Quartz	38.9	Titanite	0.8
Chlorite	2.4		
			100.0

The texture was described as a micropegmatitic intergrowth of quartz and albite, and attention was called to the frequent variation in coarseness of the implication structure, as opposed to the uniformity of the orthoclase-quartz symplectites. Holmquist compared the Gubben rock to the marginal graphic portions of the quartz-mica-porphyries of Gippsland in southeast Australia, described by Howitt.

From the archipelago outside the Nordingrå coast J. Sobral in 1913[4] published the analyses and descriptions of four sodic dikes occurring within the diabase, naming the most sodic "Värnsingite" after the island where it was found. He also mentioned the occurrence of sodic biotite-aplites and pegmatites within the gabbro on the mainland. No modes were given of the analyzed rocks, however.

On visiting the Nordingrå-Rödö area, the present author located all the above-mentioned dikes except the one represented by Table XVI in Sobral's paper and supposed to occur south of Norrsand Cove on North Ulfö island. As no specified mineral description of the dike is given by Sobral, the analysis is of small value and may be altogether omitted.

The remaining three analyses are given in the attached Analyses 3, 4, and 5. The Niggli reference values have been calculated by the author, and the actual mineral composition has been determined by geometric measurement of new slides prepared from samples taken in the immediate vicinity of the original locality. In order to check the measurements, the modes were calculated from the analyses, too. In the case of the värnsingite the mode calculated by Tröger[5] is also given.

[4] José M. Sobral, *Contributions to the Geology of the Nordingrå Region* (Upsala: University of Upsala, 1913).

[5] W. E Tröger, *Spezielle Petrographie der Eruptivegesteine* (Berlin: Deutsche mineralogische Gesellschaft, 1935).

Five new analyses have been executed from samples collected from varying dikes by the author when visiting the area Of these, the last two refer to the biotite-aplite and the pegmatite of the gabbro, mentioned by Sobral, while the three others are all from dikes within the diabase. The analyses are given in Analyses 1, 2, 6, 7, and 8. The modes were determined geometrically, using the Leitz integration stage.

For detailed mineralogical descriptions of Dikes III, IV, and V, reference is made to Sobral's excellent paper. Only the essential data are recapitulated in this paper and a few minor errors noted.

THE ALBITOPHYRE OF GUBBEN ISLAND (ANALYSIS 1)

Gubben Island is composed of doleritic diabase of the Åsby type, which is cut by semiellipsoidal or circular dikes of the white leucocratic rock which Holmquist called "albite-pegmatite." The width of the dikes exceeds the measurement given by Holmquist and occasionally reaches 2–3 feet. They seem to have been intruded into spheroidal partings arisen during the cooling of the diabase (cf. Fig. 1).

The dominant texture is micropegmatitic, grading into more coarsely granophyric. Occasionally the symplectitic intergrowth is radially grouped around idiomorphic albite-laths (cf. Fig. 2).

Sometimes, xenomorphic-granular textures with lath-shaped feldspars may be observed. Albite and quartz are the essential minerals, the albite showing checker patterns. Calcite occurs in small percentage, partly replacing the quartz in the intergrowth, partly representing the last mineral crystallized in the interstices. It is undoubtedly of primary origin. Chlorite appears accessorily, mostly as numerous small spherulitic aggregates, resembling rolls of coin. It is similar to the chlorite found in the helsinkitic granites.[6]

If the chemical and mineral composition alone are taken into account, the rock may be termed an extremely sodic quartz-albitite (Johannsen: Family 118H),[7] free from potassium. The soda-aplite, for instance, described by Brown, from South Australia, is very

[6] Harry von Eckermann, "A Find of Boulders of Helsinkite in the Parish of Alfta," *Geol. Fören. Förh.*, Vol. XLVII (1925).

[7] Albert Johannsen, *A Descriptive Petrography of the Igneous Rocks* (Chicago: University of Chicago Press, 1932), Vols. I and II.

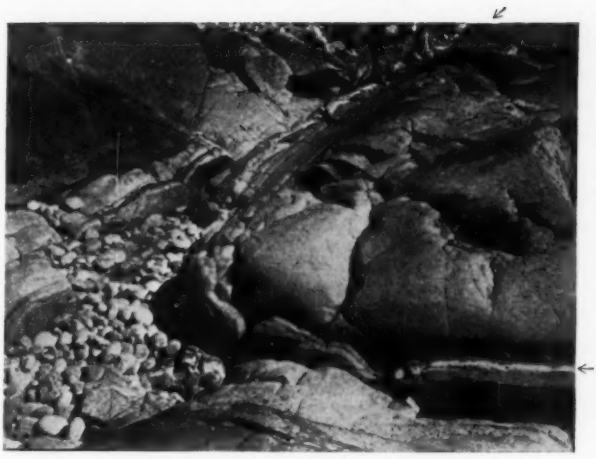


FIG. 1.—Narrow dike of albitophyre intruded into spheroidal partings of the diabase at Gubben Island. Arrows indicate position of dike.

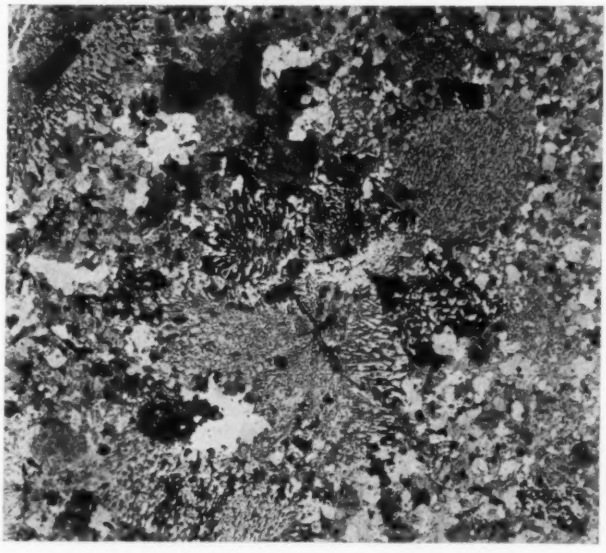


FIG. 2.—Albitophyre of Gubben Island. Crossed Nicols. ×10

similar from this point of view, but differs essentially in texture. A more or less equidimensional granular texture distinguishes the quartz-albitites, while the Gubben dikes are strikingly granophyric. Chemically this latter rock, although very acid, may almost be termed soda-syenitic and reminds one strongly of the graphic Imandrite (cf. Tröger, No. 57) from Kola. While the Imandrite, however, is explained as a hybrid product of nephelite-syenite and graywacke, the rock in question is undoubtedly a normal late-differentiate of doleritic magma.

The present author believes that the graphic texture, as opposed to the granular one of other normal sodaclase-quartz rocks, is sufficiently characteristic to justify the introduction of a special name for this new type. Albitogranophyre, for instance, would clearly indicate a rock of dominant albite in graphic intergrowth with quartz but, as a term, has the disadvantage of being rather cumbersome, especially in the use of adding prefixes to indicate the presence of essential additional minerals. Nor could it be employed in the case of those genetically connected increasingly syenitic dikes, discussed below in this paper, where calcite takes the place of quartz in the graphic intergrowth.

I have therefore thought of the abbreviated term, "albitophyre." Unfortunately, however, Coquand in 1857 introduced orthophyre and albitophyre to indicate paleovolcanic effusives containing, respectively, orthoclase- and albite-phenocrysts within an, originally, hyaline base. While the term "orthophyre" is still occasionally used in present-day nomenclature, albitophyre disappeared long ago.

The reintroduction of the latter term in a new sense is therefore not impossible but may be attended by the risk of misinterpretation as the word still suggests the sodic counterpart of the orthophyre. On the other hand, the term "orthophyre" in its original sense, even if still used in a few current textbooks, is rapidly becoming obsolete. It is not restricted to the younger effusives alone but has been used as well when describing pre-Paleozoic rocks, for instance, the Jotnian orthophyres of southern Sweden (Gavelin)[8] which rocks are ortho-

[8] Axel Gavelin, "Ett nytt postarkeiskt eruptivområde i norra Småland," *Sveriges Geol. undersökning*, Ser. C, No. 241 (1911).

clase-porphyries with extensively spherulitic or graphic groundmass textures. Actually these latter rocks are, partly at least, the textural counterpart of the sodic rest-magmas treated of in this paper.

Personally, I find it more to the purpose to use the term "orthophyre" instead of "granophyre" when speaking of primary potassic

ANALYSIS 1

ALBITOPHYRE FROM GUBBEN ISLAND
RÖDÖ ARCHIPELAGO, SWEDEN

(*Analyst:* R. Blix)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
SiO_2	78.12	130.07	Q	=37.07	Albite, An_{03}	59.7	qz	223.5	s	82.0
TiO_2	0.09	0.11	Ab	=57.68	Quartz	37.1	si	487.5	A	7.0
P_2O_5	tr.	.....	An	= 1.95	Chlorite	1.3	ti	0.38	C	0.6
Al_2O_3	12.23	12.00	C	= 0.30	Calcite	1.2	al	45.0	F	2.7
Fe_2O_3	0.26	0.16	Σ sal	97.00	Ores	0.7	fm	6.5	a	20.0
FeO	0.55	0.77	hy	= 1.09		100.0	c	7.5	c	2.0
MnO	0.02	0.03	mt	= 0.40			alk	41.0	f	8.0
MgO	0.22	0.55	il	= 0.16			mg	0.33	n	10.0
CaO	1.13	2.02	py	= 0.09			k	0.00	k	1.79
Na_2O	6.83	11.02	cc	= 1.23			c/fm	1.18		
K_2O	tr.	.....	Σ fem	2.97						
$H_2O+^{105°}$	0.20	1.11	H_2O	0.20						
CO_2	0.56	1.27		100.17						
S	0.02	0.06								
	100.23		*Quantitative system:* I:3:1:5							
$H_2O-^{105°}$	0.08		Or:Ab:An—0.00:96.73:3.27							
	100.31									

rocks of dominantly graphic texture, irrespective of geological age and porphyritic development. Porphyries with orthoclase phenocrysts should simply be called orthoclase-porphyries or orthoporphyries—the term "granophyric" only to be used in a strictly textural sense whenever quartz enters as part of a symplectitic growth. "Graphic" should cover the whole range of symplectitic textures, irrespective of mineral components.

Therefore, all disadvantages considered, I have come to the conclusion that the reintroduction of the term "albitophyre" to denote a not neccessarily porphyritic but essentially sodic rock of primary origin and dominantly graphic texture may, after all, be admissible.

THE GARNET-ALBITOPHYRE OF SVARTVIKEN COVE, NORTH ULFÖ ISLAND (ANALYSIS 2)

The rock is, in this case, slightly pink, owing partly to the presence of small (0.1–0.3 mm. in diameter) well-bounded crystals of garnet which, under the microscope, appear faintly yellow or colorless, and partly also to the pigmentation of the feldspars by iron oxide.

ANALYSIS 2

GARNET-ALBITOPHYRE FROM SVARTVIKEN COVE, NORTH ULFÖ

(*Analyst:* N. Sahlbom)

	Percentage	Mol. Prop. ×100	Norm	Mode	Percentage	Niggli's System		Osann's System	
SiO_2	75.95	126.46	Q = 37.05	Albite, $Or_{02}An_{06}$	53.8	qz	+187	s	81.4
TiO_2	0.12	0.15	Or = 1.65	Quartz	37.1	si	439	A	6.2
P_2O_5	0.00	.....	Ab = 48.75	Garnet	8.8	ti	0.69	C	1.6
Al_2O_3	12.33	12.10	An = 6.95	Ores	0.3	al	42.0	F	3.0
Fe_2O_3	1.67	1.05	Σ sal = 94.40		100.0	fm	9.5	a	17.0
FeO	0.27	0.38	di = 0.46			c	15.5	c	4.5
MnO	0.04	0.06	wo = 2.09			alk	33.0	f	8.5
MgO	0.09	0.22	il = 0.25			mg	0.07	n	9.7
CaO	2.54	4.53	mt = 0.64			k	0.03	k	1.87
Na_2O	5.75	9.28	hm = 1.21			c/fm	1.61		
K_2O	0.27	0.29	Σ fem = 4.65						
$H_2O+^{105°}$	0.84	4.66	H_2O 0.84						
BaO	0.00	.....	99.89						
F	0.00	.....							
CO_2	0.00	.....							
	99.87		*Quantitative system:* I:3:2:5						
$H_2O-^{105°}$	0.20		Or:Ab:An—2.88:85.00:12.12						
	100.07								

The dominant minerals are graphically intergrown checkered albite and quartz. As no mica or orthoclase is observable, the slight potash-content may be presumed to enter the albite as Or-molecules.

No calcite is present, but tiny flakes of chlorite occur as an alteration product of the garnet. A few small titanite crystals and some titano-magnetite were also observed.

Compared with the albitophyre of Gubben Island, the amount of quartz is equal, while the albite percentage is slightly lower. The considerably higher percentage of chemically combined water is not

traceable in the mineral combination, but the replacement of chlorite by garnet may indicate a crystallization at higher internal pressure.

Only one dike of 20 cm. width has been observed, cutting straight through the diabase close to the shoreline (cf. Fig. 3).

FIG. 3.—Dike of garnet-albitophyre at Svartvike Cove, North Ulfö Island

THE PYROXENE-ALBITOPHYRE OF SVARTVIKEN COVE NORTH ULFÖ ISLAND (ANALYSIS 3)

The rock occurs as grayish sinuous dikes south of the garnet-albitophyre. The dominant mineral is albite in graphic implication with quartz and pyroxene. Calcite, titanite, magnetite, and apatite occur as accessories. Some muscovite flakes are found within the albite and especially along the contacts toward the quartz implications. The pyroxene has crystallized in two generations—an older one, represented by idiomorphically bounded grains, and a younger one, represented by the allotriomorphic intergrowth.

Sobral has drawn attention to the surprisingly great amount of

CaO in the analysis although no lime-feldspar is present. Consequently, the pyroxene must of necessity be rich in lime. Sobral believed it to be a variety of the augite occurring in the diabase and observed, too, its ready alteration into a greenish-brown fibrous substance. This alteration corresponds to that observed by the present author in the diopsidic pyroxenes of monzonitic diabases within the Hamra region[9] but here is more greenish.

ANALYSIS 3

AUGITE-ALBITOPHYRE, IMMEDIATELY SOUTH OF SVARTVIKEN COVE, NORTH ULFÖ

(*Analyst*: N. Sahlbom)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
SiO_2	70.75	117.92	Q	19.82	Albite, Or_{08}	62.6	qz	+77	s	75.3
TiO_2	0.17	0.21	Or	4.67	Quartz	20.0	si	305	A	7.93
P_2O_5	0.10	0.07	Ab	57.27	Augite	16.0	ti	0.52	C	0.00
Al_2O_3	12.01	11.77	Σ sal	81.70	Calcite	0.9	al	30.5	F	9.27
Fe_2O_3	0.62	0.39	ac	1.80	Apatite		fm	28.0	a	14.0
FeO	0.94	1.31	di	6.02	and ores	0.5	c	9.5	c	0.0
MnO	0.08	0.11	hy	0.35		100.0	alk	32.0	f	16.0
MgO	0.56	1.40	wo	8.35			mg	0.39	n	9.22
CaO	6.13	10.95	il	0.32			k	0.06	k	1.33
Na_2O	7.20	11.61	ap	0.22			c/fm	3.05		
K_2O	0.79	0.84	cc	0.91						
$H_2O+^{105°}$	0.49	2.72	Σ fem	17.98						
S	tr.	tr.	H_2O	0.49						
CO_2	0.40	0.91		100.17						
BaO	tr.	.....								
	100.24	*Quantitative system:* II:4:3:5								
$H_2O-^{105°}$	0.20	Or:Ab:An—7.56:92.44:0.00								
	100.44									

Several attempts were made by the present writer to determine the nature of the alteration, but the fibrous texture prevents accurate optical readings. I have come to the conclusion, however, that the composition is mainly one of wollastonite intergrown with fibers of urbanitic amphibole. This, too, would correspond nicely with the "normal" values which Sobral could not bring into agreement with the analysis. The brownish-gray fibrous substance replacing the diopsidic pyroxene of the monzonitic diabase of Vassjöån

[9] Von Eckermann, "The Loos-Hamra Region," *op. cit.*, p. 315.

Brook (Hamra region), previously described by the present author[10] as chloritic, was also re-examined. The presence of chlorite was confirmed, but its intergrowth with a grayish or colorless fibrous mineral was found to have been overlooked. This latter mineral was found to be prehnite.

The outstanding chemical difference between the analysis of the monzonitic diabase and that of the pyroxene-albitophyre is the al-alk ratios, which in the former rock is 2.10 while in the latter it is only 0.95. At the same time, the diabase is rich in chemically bound water, 2.88 per cent, while the albitophyre contains 0.49 per cent. One may, consequently, in the first case expect an alteration product of more or less hydrous minerals, rich in alumina, while, in the latter instance, the new minerals would be "dry" and poor in alumina. This is in agreement with the mineral combinations actually observed: prehnite-chlorite and wollastonite-urbanite, respectively.

In both cases, however, the dominant lime-component of the resulting autometamorphism suggests an original pyroxene composition, where the molecular ratio of CaO was considerably in excess of that of the (Mg, Fe)O. This leads to the interesting suggestion of a "diopsidic" ratio $CaO : MgO > 1$ being stable at higher temperature and pressure.

GARNET-ALBITITE SOUTH OF NORRSAND COVE NORTH ULFÖ ISLAND (ANALYSIS 4)

This dike-rock is fine-grained, somewhat porphyritic, and of a pale-reddish color, due to pigmentation of the albite. The texture is granular. The dominant minerals are checkered albite and light brownish-yellow garnet of grossularitic composition. As accessory constituents occur quartz, diopside, magnetite, ilmenite, apatite, titanite, calcite, muscovite, chlorite, hornblende, chabazite and epidote.

Sobral points out that the garnet is not quite isotropic, but he has overlooked the fact that the birefringence is mostly due to poikilitically intergrown diopsidic pyroxene.

The rock is a syenitic modification of the garnet-albitophyre of Analysis 2, but lacks graphic texture. It is an albite-aplite, poor

[10] *Ibid.*, Pl. XCIV.

in quartz, and in this case the term "albitite," proposed by Turner in 1896, seems appropriate in conjunction with the prefix "garnet."

The rock is typically aplitic—all the accessory minerals, except quartz and muscovite-chlorite, occurring in small amounts. The percentages of quartz and calcite vary somewhat, and both minerals

ANALYSIS 4

GARNET-ALBITITE, SOUTH OF NORRSAND COVE
NORTH ULFÖ ISLAND
(*Analyst:* N. Sahlbom)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
SiO_2	60.19	100.32	Q	1.76	Albite	64.6	qz	− 5	s	67.1
TiO_2	0.50	0.62	Or	5.23	Garnet and diopside	21.5	si	201	A	8.70
P_2O_5	0.07	0.05	Ab	63.67	Muscovite and chlorite	6.8	ti	1.20	C	0.73
Al_2O_3	14.47	14.19	An	3.06	Quartz	4.8	al	28.5	F	14.04
Fe_2O_3	2.53	1.58	Σ sal	73.72	Ores	1.2	fm	31.0	a	11.0
FeO	0.78	1.08	di	11.92	Calcite	0.9	c	14.0	c	1.0
MnO	0.06	0.08	hy	5.60	Apatite	0.2	alk	26.5	f	18.0
MgO	4.45	11.12	mt	1.25		100.0	mg	0.72	n	9.28
CaO	3.80	6.79	hm	1.66			k	0.07	k	0.99
Na_2O	7.53	12.15	il	0.94			c/fm	0.45		
K_2O	0.88	0.94	ap	0.15						
$H_2O+^{105°}$	3.16	17.54	Σ fem	21.52						
BaO	tr.	.....	H_2O	3.16						
S	tr.	.....		98.40						
CO_2	0.38	0.86								
	98.80	*Quantitative system:* II:5:2:5								
$H_2O-^{105°}$	1.14	Or:Ab:An—7.26:88.49:4.25								
	99.94									

represent the closing stage of crystallization. The muscovite and chlorite are autometamorphic hydration products of an originally stable Or content in the albite and of the original ferromagnesian minerals, respectively.

THE PYROXENE-ALBITITE (VÄRNSINGITE) OF WEST VÄRNSINGEN ISLAND (ANALYSIS 5)

The rock occurs as short, narrow, coarse-grained white dikes on the eastern shore of the western of the two small islands. The texture is granular. It consists of large crystals of albite, irregularly intergrown poikilitically with rounded grains of a brownish-greenish

augite similar to the titanium-augite of the Åsby diabase. The albite also includes numerous idiomorphic crystals of titano-magnetite, often accompanied by nicely crystallized titanite. Apatite is conspicuously present. Accessorily, there occur small quantities of quartz, epidote, prehnite, chlorite, amphibole, and muscovite.

ANALYSIS 5

PYROXENE-ALBITITE (VÄRNSINGITE) FROM WEST VÄRNSINGEN ISLAND, NORDINGRÅ

(*Analyst:* N. Sahlbom)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
					Measured:					
SiO_2	56.33	93.88	Q	0.63	Albite An_{03}	64.6	qz	− 22	s	62.7
TiO_2	1.76	2.20	Or	2.28	Augite	26.0	si	152	A	6.82
P_2O_5	0.96	0.68	Ab	52.92	Titanite	2.6	ti	3.80	C	3.55
Al_2O_3	16.25	15.93	An	15.07	Apatite	2.4	al	27.5	F	16.53
Fe_2O_3	1.22	0.76	Σ sal	70.90	Ores	1.7	fm	32.5	a	7.5
FeO	3.46	4.81	di	10.54	Epidote, prehnite, mica	1.5	c	21.5	c	4.0
					Quartz	1.2	alk	18.5	f	18.5
MnO	0.13	0.18	hy	10.01		100.0	mg	0.65	n	9.60
MgO	4.89	12.22	mt	1.76			k	0.04	k	0.97
CaO	6.92	12.36	il	2.34	*Calculated by Tröger:*		c/fm	0.71		
Na_2O	6.26	10.10	ap	2.11						
K_2O	0.39	0.41	Σ fem	27.76	Albite An_{05}	66.0				
$H_2O+^{105°}$	0.80	4.44	H_2O	0.80	Augite	27.0				
S	tr.	.....		99.46	Titanite, apatite, ores, epidote, muscovite ±Quartz	7.0				
BaO	0.00	.....								
$H_2O-^{105°}$	0.15	*Quantitative system:* II:5:3:5								
	99.52	Or:Ab:An—3.24:75.34:21.50								

Sobral called the värnsingite a type of diabase-pegmatite, and Tröger terms it an augite-albite-pegmatite, related to the alkali-syenites. In conformity with the nomenclature established in the present paper it should be called a pyroxene-albitite-(pegmatite).

The Värnsingite magma does not seem to have moved any great distance within the diabase. The rock is rather salic in the center of the dikes, while the mafic minerals increase in amount toward the contacts which, occasionally, are blurred. This signifies that the

sodic rest-differentiate solidified when the surrounding diabase was still at a comparatively high temperature, which suggests a differentiation almost *in situ*.

SVARTVIKITE (MUSCOVITE-CALCITE-ALBITOPHYRE) OF SVARTVIKEN COVE, NORTH ULFÖ ISLAND (ANALYSIS 6)

Close to the garnet-albitophyre of Analysis 2, a narrow grayish dike, about 20–30 cm. wide, was found cutting straight through the diabase. The texture is graphic, and the dominant mineral is albite

FIG. 4.—Svartvikite. Intergrowth of muscovite (calcite) and albite (gray). The dark patches are diopside and ores. Ordinary light. ×33.

intergrown with muscovite and calcite. A fair percentage of greenish-yellow diopsidic pyroxene occurs as idiomorphic or rounded grains within the albite (cf. Fig. 4).

The albite is mostly of checker pattern. The calcite, alternating with the muscovite in the implication texture, is undoubtedly of primary origin. Chemically, the rock is—in the nomenclature of Tröger—oligoclasitic-carbonatitic, and the analysis closely resembles that of Holyokeite of Massachusetts (Emerson, 1902). Mineralogi-

cally, however, in this case the potash molecules form muscovite instead of the orthoclase of the Holyokeite.

In correspondence with the present author's nomenclature the rock should be termed a "muscovite-calcite-albitophyre"—a somewhat cumbersome name to use. As the rock is of a distinctly new species, hitherto, as far as the present author has been able to ascer-

ANALYSIS 6

SVARTVIKITE (MUSCOVITE-CALCITE-ALBITOPHYRE)
FROM SVARTVIKEN COVE, NORTH ULFÖ ISLAND
(*Analyst:* H. von Eckermann)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
SiO_2	54.66	91.01	Or	16.71	Albite, An_{01}	59.9	qz	− 29	s	59.7
TiO_2	0.05	0.06	Ab	58.73	Muscovite	23.5	si	183	A	9.3
P_2O_5	0.00	.....	An	6.67	Calcite	11.2	ti	0.20	C	4.1
Al_2O_3	20.74	20.35	C	3.87	Diopside	4.9	al	41.0	F	13.5
Fe_2O_3	0.16	0.10	Σ sal	85.98	Ores	0.5	fm	4.0	a	10.5
FeO	0.58	0.81	ol	1.43		100.0	c	27.0	c	4.5
MnO	tr.	.....	mt	0.24			alk	28.0	f	15.0
MgO	0.46	1.15	il	0.12			mg	0.57	n	7.9
CaO	7.63	13.61	cc	11.22			k	0.21	k	0.77
Na_2O	6.95	11.21	Σ fem	13.01			c/fm	6.48		
K_2O	2.84	3.02	H_2O	1.17			CO_2	22.51		
$H_2O+^{105°}$	1.17	6.49		100.16						
CO_2	4.94	11.23								
	100.18	*Quantitative system:* II:5:2:2								
$H_2O-^{105°}$	0.31	Or:Ab:An—20.25:71.53:8.12								
	100.49									

tain, not described from anywhere else, the writer may perhaps be allowed to distinguish it by a name of its own: Svartvikite.

The Svartvikite magma at its moment of congealing evidently had a deficiency of silica, which prevented the crystallization of orthoclase, but possessed an excess of water, which led to the formation of mica. Although its albite content, about 60 per cent, is of the same order as that of the previously described sodic dikes, the considerably higher potash percentage constitutes an important and interesting departure. It may indicate a relationship to a mother-magma of less sodic character than the diabase. This is illustrated, too, by its position in the Or-Ab-An diagram (cf. Fig. 5) and its

inconsistency with the Niggli diagram of the other dikes (cf. Fig. 8). Such a mother-magma would be the monzonitic diabase of the region. On the other hand, there is no field evidence to support such an assumption.

THE DIKES WITHIN THE NORDINGRÅ GABBRO

These white, partly aplitic, partly pegmatitic, rocks are generally observed intersecting the gabbro as more or less inclined thin sheets, rarely dipping more than 45°. They occur in swarms, suggesting in-

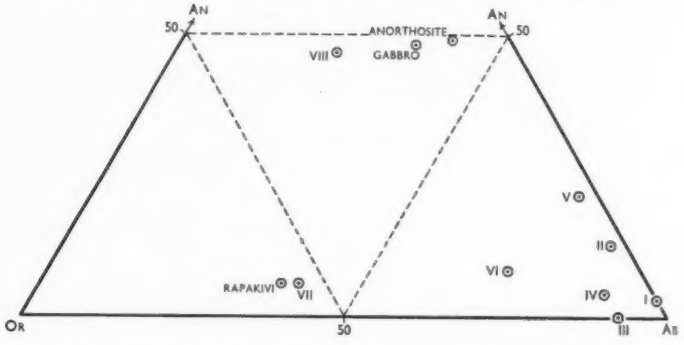


FIG. 5.—OR-AB-AN diagram. Numbers refer to the analyses of this paper. The anorthosite, gabbro, and rapakivi-granite are entered from unpublished analyses from the Nordingrå region.

trusions into contraction fissure-zones developed parallel to the upper cooling surface of the gabbro, or close to the contact against older Archean rocks.

Two main types of dikes are noticeable—the one characterized by small biotite flakes, the other by the absence, megascopically, of any colored minerals. The latter are more coarse-grained, almost pegmatitic. They have the appearance of being rest solutions further differentiated than those of the biotite-bearing dikes. They grade occasionally into fine-grained micropegmatitic leucocratic rocks.

THE BIOTITE-SODACLASE-APLITE WEST OF VENNERSTA NORDINGRÅ (ANALYSIS 7)

The mineral composition of this rock is dominantly microperthitic orthoclase and albite, a fair amount of quartz, and some

biotite, the latter mostly autometamorphosed into chlorite. Accessories are titano-magnetite and apatite. The texture is saccharoidal, with a tendency to the formation of orthoclase-phenocrysts, which crystallized earlier than the albite.

Chemically, this rock displays a marked differentiation toward granitic composition and seems to occupy an intermediate position

ANALYSIS 7

BIOTITE-SODACLASE-APLITE, WEST OF VENNERSTA, NORDINGRÅ

(*Analyst:* N. Sahlbom)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
SiO_2	69.06	114.99	Q	17.30	Albite, An_{13}	35.0	qz + 77		s	76.6
TiO_2	0.45	0.56	Or	40.61	Orthoclase	36.2	si	325	A	8.6
P_2O_5	0.19	0.13	Ab	29.90	Biotite	7.4	ti	1.70	C	1.0
Al_2O_3	14.72	14.44	An	4.15	Quartz	19.9	al	41.0	F	4.2
Fe_2O_3	0.10	0.06	Σ sal	91.96	Ores	1.1	fm	13.5	a	18.5
FeO	2.34	3.26	di	2.86	Apatite	0.4	c	8.5	c	2.5
MnO	0.01	.....	hy	3.36		100.0	alk	37.0	f	9.0
MgO	0.56	1.39	ap	0.41			mg	0.29	n	4.2
CaO	1.66	2.96	il	0.87			k	0.56	k	1.32
Na_2O	3.56	5.74	mt	0.17			c/fm	0.63		
K_2O	6.89	7.31	Σ fem	7.67						
$H_2O+^{105°}$	0.60	3.33	H_2O	0.60						
				100.23						
	100.23	*Quantitative system:* I:4:1:3								
$H_2O-^{105°}$	0.16	Or:Ab:An—54.39:40.05:5.56								
	100.39									

between nordmarkitic magmas, rich in potash, and grano-syenitic magmas. The equal distribution of potassic and sodic feldspar reminds one of quartz-monzonitic magmas, but the An content is too low to justify the use of this term. Actually, there is no term in present-day nomenclature which adequately applies to the present rock. Its plutonic equivalent would in Johannsen's nomenclature be a sodaclase-granite (216P) or sodaclase-granodiorite (217P).

Calling it simply a biotite-aplite suggests an aplitic differentiate of a potassic granitic magma, whereas in the present case we have to deal with an acid intermediate rest-differentiate of a gabbro. In agreement with Johannsen's classification, I, therefore, here tenta-

tively apply the name "biotite-sodaclase-aplite," indicating a rock containing orthoclase and sodaclase.

In the Or-Ab-An diagram, the biotite-sodaclase-aplite occupies a position coinciding with that of the rapakivi granites, and in the Niggli diagram a similar position agreeing with that of the syenitic rapakivis (cf. Figs. 5 and 8).

THE PREHNITE-SODACLASE-PEGMATITE SOUTH OF JERESTA NORDINGRÅ (ANALYSIS 8)

These pegmatitic leucocratic dikes within the gabbro have a very peculiar composition, chemically as well as mineralogically. To pre-

ANALYSIS 8

PREHNITE-SODACLASE-PEGMATITE
SOUTH OF JERESTA, NORDINGRÅ
(*Analyst:* N. Sahlbom)

	Percentage	Mol. Prop. ×100	Norm		Mode	Percentage	Niggli's System		Osann's System	
SiO_2	57.20	95.24	Q	8.04	Prehnite	49.0	qz + 12		s	63.9
TiO_2	0.00	.....	Or	21.12	Orthoclase	23.8	si	166	A	4.9
P_2O_5	0.00	.....	Ab	18.40	Albite	20.1	ti	0.00	C	8.3
Al_2O_3	20.06	19.68	An	34.49	Quartz	6.3	al	36.5	F	9.7
Fe_2O_3	0.20	0.13	Σ sal	82.05	Chlorite	0.8	fm	1.5	a	6.5
FeO	0.19	0.27	di	0.90		100.0	c	48.5	c	11.0
MnO	0.01	0.01	wo	14.95			alk	13.5	f	12.5
MgO	0.07	0.17	mt	0.27			mg	0.29	n	4.9
CaO	14.70	26.21	Σ fem	16.12			k	0.52	k	0.87
Na_2O	2.17	3.50	H_2O	2.4			c/fm	37.43		
K_2O	3.56	3.78		100.31						
$H_2O+^{105°}$	2.14	11.88								
BaO	tr.	.....								
CO_2	0.00	.....								
	100.30		*Quantitative system:* II:5:4:3							
$H_2O-^{105°}$	0.22		Or:Ab:An—28.54:24.86:46.60							
	100.52									

clude any mistake, the percentages of alumina and lime have been checked by Dr. Sahlbom by a repeated analysis of another sample, obtaining: Al_2O_3 = 20.16 per cent and CaO = 14.86 per cent.

The dominant mineral is prehnite, forming almost 50 per cent of the rock—the remaining important constituents being micro-perthitic orthoclase, albite, and some quartz. A pale-green chlorite occurs accessorily.

The orthoclase was the first mineral to crystallize in well-bounded phenocrysts. It was followed by the prehnite, which surrounds the

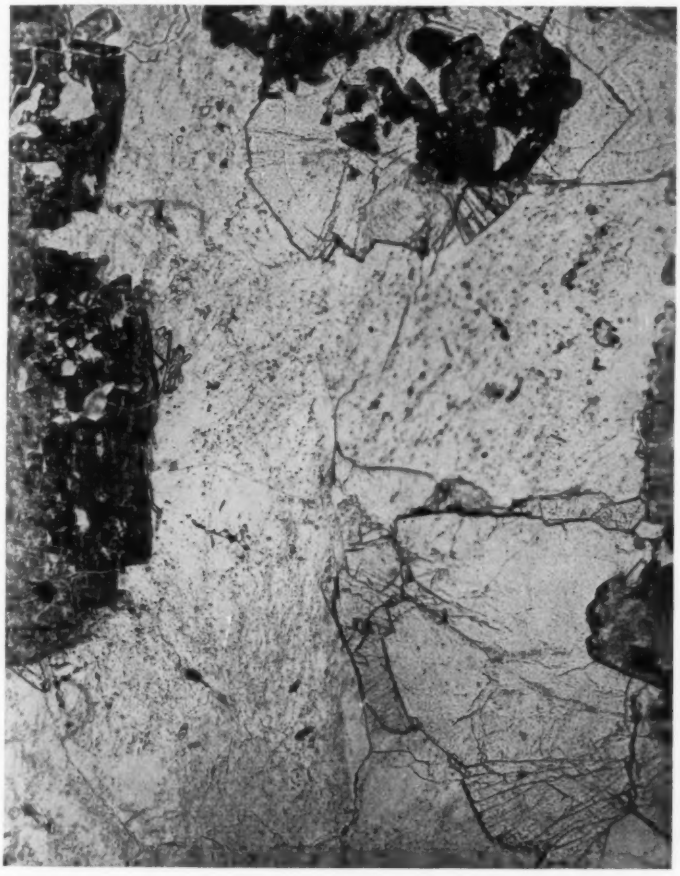


FIG. 6.—Prehnite-sodaclase-pegmatite. The dark-gray mineral is orthoclase; the light-gray mineral of strong relief, prehnite; and the rest, albite. Ordinary light. ×20.

orthoclase crystals in beautiful radial growth. The last crystallized minerals, filling up the interstices, are the albite and some prehnite (cf. Fig. 6). This is rather contrary to the usual sequence of crystal-

lization, where the prehnite generally occupies the interstices. The explanation of this reversal of the usual order must be sought for partly in the overwhelming concentration of CaO molecules, following upon the precipitation of the orthoclase, and partly in the presence of a high percentage of high-tension water vapor. This is confirmed in the case of the associated less pegmatitic and calcic dikes, discussed below, in which the bulk of the prehnite is found in the interstices.

Chemically, the composition of the rock is almost that of a very potassic anorthosite, poor in iron and magnesia. Its consolidation must have occurred at temperatures bordering on the hydrothermal range, but it is nevertheless interesting, as it indicates a late differentiation similar to that of anorthositic magma out of gabbro. The present author has recently investigated the relationship between the gabbros and the anorthosites of Nordingrå, and, even if this subject lies outside the scope of this paper, it may be pertinent to draw attention to the similarity between the Niggli values of the anorthosites and those of the present dike-rock.

The former have been found to be:

al	37.5	c	29.0
fm	20.0	alk	13.5

while the latter are:

al	36.5	c	48.5
fm	1.5	alk	13.5

The difference lies in the fm:c ratios, resulting from the differentiation of a gabbro of the following values:

al	24.0	c	19.5
fm	48.0	alk	8.5

While the plutonic gravitative differentiation of the anorthosites tends to an equalization of the fm-c values, the peri-magmatic differentiation encompasses a selective concentration of the lime at coincident increases in al and alk values.

It is not easy to find an adequate name for this peculiar dike-rock. In accordance with the naming of the biotite-sodaclase-aplite, Analysis 6, I tentatively propose "prehnite-sodaclase-pegmatite."

THE SODACLASE-RUNITE

As mentioned above the "prehnite-sodaclase-pegmatite" grades into a less calcic rock, constituting a less extreme differentiate. No analysis of these parts of the dikes has been executed, but the mode was determined geometrically as follows:

	Per Cent		Per Cent
Orthoclase	44.6	Prehnite	5.8
Albite	26.4	Chloritized biotite and titanite	0.5
Quartz	22.7		
			100.0

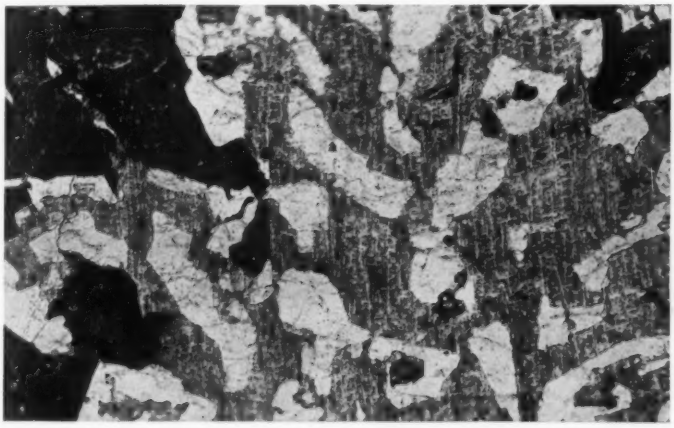


FIG. 7.—Sodaclase-runite. The dark mineral is orthoclase; the gray, albite; and the light-gray, quartz. Ordinary light. ×33.

The texture is of the peculiar micrographic type of the Runites (Johannsen: Family 111D). While the latter consist essentially of quartz and potash-feldspar, the feldspar component in the present case is one of, roughly, two-thirds albite and one-third orthoclase. Both feldspars are jointly intergrown with patches of quartz extinguishing at the same time between crossed nicols (cf. Fig. 7).

The orthoclase—which may be somewhat microperthitic, the pigmentation preventing accurate microscopical determination—shows idiomorphic tendencies but is generally intergrown micrographically with the albite. In this rock, therefore, a peculiar three-phase inter-

growth of Ab-Or-Qu is present, showing the following weight proportions, respectively: 47.6:28.1:24.3.

It is of interest to note that the quartz proportion is of the same order as in the ordinary runites (cf. Johannsen's *Petrography*, II, 85). This confirms Vogt's supposition, quoted by Johannsen, that the eutectic Qu:Ab holds about the same percentage of Qu as the eutectic Qu:Or, owing to the fact that the melting-point, the melting heat, and the molecular weight are nearly the same. The present ternary eutectic may, consequently, be considered almost a binary one, as the Or and Ab seem to replace each other without influencing appreciably the Qu ratio.

I propose to name this rock "sodaclase-runite." Even if the sodaclase-runite may not represent the intermediary magmatic solution from which the prehnite-sodaclase-pegmatite has originated, but constitutes presumably a "counterdifferentiate" resulting from the splitting-up of the magma, it nevertheless emphasizes an interesting departure from the usual mode of pegmatitic differentiation. Whereas, in the case of the granites, the pegmatites become increasingly acid, the ultimate pegmatitic solutions of the present dikes are characterized by decreasing silica, and increasing lime, content.

CONCLUDING REMARKS

The analyses, published above, are merely a first step toward the elucidation of the mechanism of late differentiation within the basic magmas of doleritic and gabbroic composition. They are not even sufficient for a full chemical illustration of the evolution within the restricted magmatic province they represent. More facts must be gathered, both in the field and in the laboratory, before any definite conclusions are permissible.

The evidence, now presented, shows, however, that the late-magmatic differentiation within the Nordingrå-Rödö region is a different one within the diabases and the gabbros.

Within the former it leads to sodic differentiates of an almost stable percentage of about 60 per cent albite, whereas the potash content is generally negligible, or totally absent in the most acid rest-magmas. Where the potash is present, it enters the mineral

components as autometamorphic muscovite, precipitated within the sodaclase.

Only in the most basic differentiates, free of quartz, has an appreciable percentage of potash (muscovite) been observed in combination with abundant calcite. In this case, the mica occurs as a primary mineral. Generally, however, the amount of primary calcite is limited to about one per cent.

The FeO-MgO minerals, in combination with the CaO, not contained in calcite, show a variety of developments. In the acid differentiates (37 per cent free silica) they combine either as chlorite (helsinkitic phase) or as garnet. In both cases the graphic textures suggest eutectic rest-solutions. In dike-magmas of lesser acidity they are represented by either augite, diopside, or garnet; the reason of the one or the other development being still obscure. The autometamorphic transformation of diopsidic augite into wollastonite indicates, in the case of the Värnsingite, unusual stability relations during the initial period of differentiation.

Compiled into a Niggli diagram, the analyses of the dike-rocks of the diabases do not present very smooth curves, but the general trend of differentiation is, nevertheless, clearly indicated. Excluding Analysis 6, it is mainly Analysis 3 of the pyroxene-albitophyre, which disturbs the smoothness of the curves, mostly those of "c" and "fm" values (cf. Fig. 8). The Niggli values of Analysis 6 of the Svartvikite are quite incompatible with those of the other two analyses, which seems to indicate that the differential sequence may have been a different one. On the other hand, combined field and microscopical evidence has established an abrupt but, nevertheless, unbroken transition from rocks very similar to the pyroxene-albitites into the Svartvikite. This is borne out if one enters not the Niggli values but the weight percentages of the different components of the rocks in an SiO_2 diagram (cf. Fig. 9). Analysis 6 will then occupy the position of the most basic member of the suite and may be connected with the curves of the other rocks. Even then its peculiar position is emphasized by the sudden drop of the (Fe, Mn, Mg)O-curve and the sudden rise of the alumina-, lime-, and alkali-curves.

There is a certain similarity between this sudden reversal of the

curves within a narrow SiO_2 range and the anorthositic differentiation of the prehnite-sodaclase-pegmatite, remarked upon above. Increased pegmatitic habit (concentration of volatiles) leads in this case, however, to a concentration not only of lime but also of potash.

Within the gabbros, the late rest-magmas follow two distinct trends of differentiation, one increasingly acid, accompanied by decreasing lime, and one less acid, accompanied by enormously increased lime content. In both cases the orthoclase-sodaclase ratio

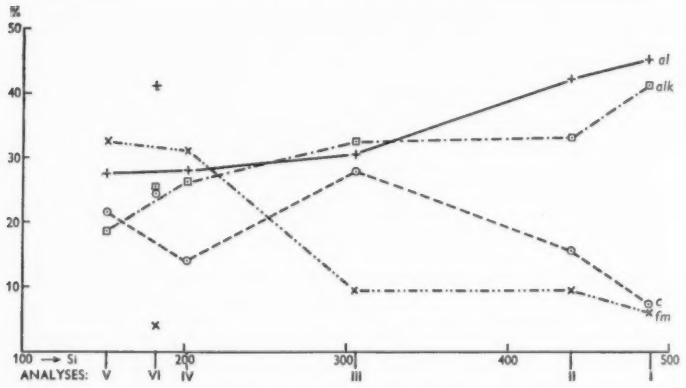


FIG. 8.—Niggli diagram of the sodic dikes of the diabase

remains stable at about unity, although the total amount of alkalies decreases as the lime component increases. While the biotite component of the acid differentiate suggests a comparatively high temperature, the prehnite and acccessory chlorite of the basic differentiate indicate an almost hydrothermal congealing temperature (helsinkite phase). The former differentiation has a granitic tendency, leading chemically to an Or:Ab:An ratio of rapakivic composition (cf. Fig. 5); the latter duplicates the lime concentration of the anorthositic evolution, leading chemically to a hydrated anorthositic composition.

In the Niggli diagram (Fig. 10), there are entered Analyses 7 and 8 as well as the values of the anorthosite and the gabbro of the region, established by the present author. The prehnite-sodaclase-pegmatite has been connected by curves with the anorthosite; the

biotite-sodaclase-aplite with the gabbro. The values of the rapakivi of Loberget Hill (Loos-Hamra region)[11] are also given as comparison.

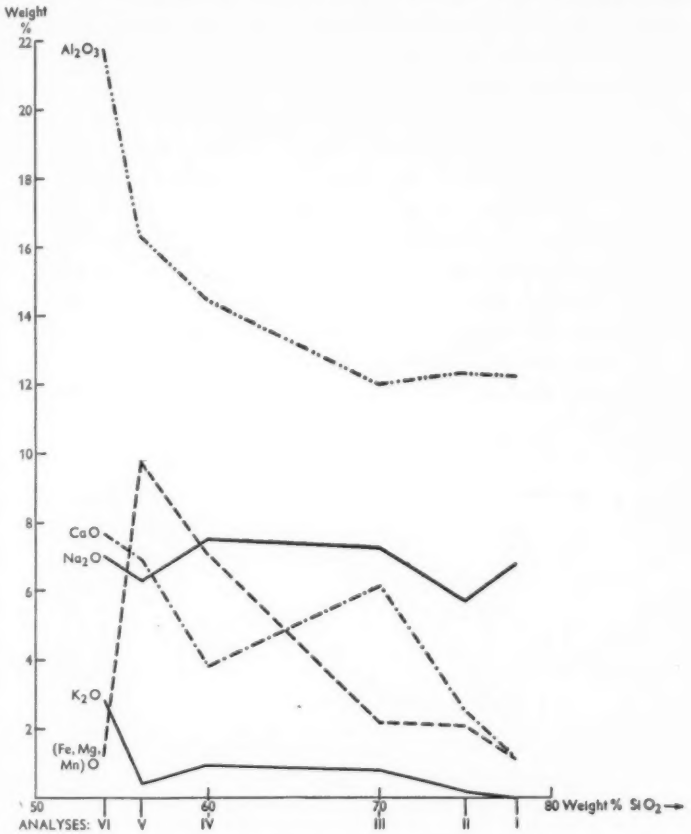


FIG. 9.—Variation diagram of the dikes within the diabase

While the gabbro–sodaclase-aplite curves closely resemble normal differentiation lines toward rapakivic magma, the anorthosite–sodaclase-pegmatite curves indicate, so to say, an enhanced anorthositic differentiation within a comparatively narrow si-range.

[11] *Ibid.*, p. 295.

While "al" and "alk" remain stable, "c" increases considerably and "fm" decreases correspondingly. There is no way yet of telling whether the latter rest-differentiates are derived directly from the gabbro—in which case there would be a still greater rational increase in "c" and drop in "fm"—or secondarily from the anorthosite. The sodaclase-runite, however, suggests the former alternative.

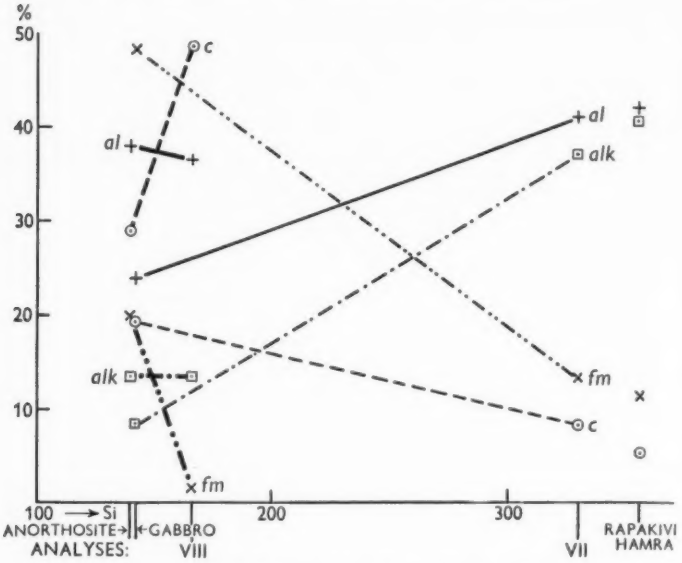


FIG. 10.—Niggli diagram of the dikes within the gabbro

The reason why the late pegmatitic differentiation in the case of the gabbro leads to lime concentration and in the case of the genetically connected diabase to alkali (potash-lime) concentration is obscure. At present, one has to rest content with the finding of the facts. Although chemically of very similar or even almost equal composition, the one mother-magma is plutonic while the other is hypabyssic or effusive. Consequently, the pressure and temperature governing the stability relations were certainly different as may have been the content and composition of the volatiles active at the time of solidification.

Many more rocks, representing intermediate positions on the respective lines of differentiation must be found and investigated before the short end-stumps, now established by the present author, can be properly connected with their respective mother-magmas. Not until then will the possibility arise of a definite understanding of the conditions governing the development of these rest-solutions. Another question awaiting its answer is the reason why some great masses of diabase are rich in sodic rest-differentiates while others of the same magnitude and the same age, such as, for instance, the Dalecarlia rocks, show no corresponding development.

Finally, the author wishes to emphasize the general importance of looking for "missing links" within tectonically undisturbed areas as, for instance, the Swedish Jotnian. Thereby the risk of mistakes, caused by fluid portions of crystallizing magma squeezed out by tectonic motions being taken for rest-differentiates *in situ*, may be avoided.

EKLOGIT IM SCHWARZWALD UND SEINE RETROGRADE UMWANDLUNG

O. H. ERDMANNSDÖRFFER
Heidelberg

DAS VORKOMMEN

Während in anderen deutschen Mittelgebirgen wie Erzgebirge, Fichtelgebirge echte Eklogite häufig sind, kennt man sie im Schwarzwald kaum. In den Erläuterungen zu der geologischen Spezialkarte von Baden ist meist nur von "eklogitähnlichen" Gesteinen die Rede. Rosenbusch bildet in seinen *Elementen der Gesteinslehre* einen "Eklogit" vom Silberberg bei Hinterzarten ab. Da dies Gestein gut aufgeschlossen ist und interessante Züge aufweist, wird hier eine nähere Beschreibung gegeben. Auf die umfangreiche Eklogitliteratur werde ich an anderer Stelle eingehen.

Der Gesteinskomplex bildet eine plumpe in NNO-SSW gestreckte Linse von etwa 20 × 30 m Ausdehnung. Nördlich anstossend stehen "körnig-streifige," lokal mit Quarzlagen verknetete Gneise an, die 73–84° O streichen und, mehrfach gewellt, steil Süd fallen ("liegender Kontakt"). Im Hangenden liegen, einige m südlich des Bruches selbst, zunächst auf dem "Eklogit" weisse aplitähnliche Gesteine mit 74° O Streichen und flachen (*ca.* 16°) Südfallen. Einige m oberhalb der Grenze werden sie glimmerreicher und enthalten bis mehrere dm mächtige Linsen von derbem weissen Quarz. Nach N hin wird das Streichen des hangenden Gneises steiler (N 38 O bei steilem SO Fallen) und schmiegt sich weiterhin den Gneisen des Liegenden an.

Am direkten Kontakt mit dem Gneis treten an Stelle des "Eklogits" und mit ihm durch Übergänge verknüpft, dunkle biotitreiche Gesteine. Diese werden mehrfach von 1½ cm bis mehrere dm mächtigen hellen, teils aplitartigen, teils grobpegmatitischen Trümern durchsetzt und auch in z.T. linsenförmig gestalteten Stücken umschlossen. Im Hangenden sind die Verhältnisse ähnlich, doch fehlt hier der Pegmatit. Die Grenze hell-dunkel ist scharf. Von den mannigfachen Klüften, die das Ganze durchsetzen, fallen besonders

scharfe N–S verlaufende und 60° O fallende durch ihre Füllung mit rein weissem grobkörnigem Feldspat-Quarzgemenge auf. Die übrigen Klüfte—z.T. O–W verlaufend—sind ohne Füllung.

Der gesamte "Eklogit"-Komplex gliedert sich folgendermaßen: Im Kern der Linse stecken die dem Rosenbusch'schen Handstück entsprechenden Gesteine. Nach außen hin gehen sie in einen, den Hauptanteil des Ganzen bildenden dunkelgrünen Granatamphibolit über. Beide Arten sind nicht völlig homogen, sondern umschliessen ohne scharfe Grenzen linsenförmige oder unregelmäßig gewellte helle und z.T. recht quarzreiche Partien. Die N–S Klüfte setzen auch durch diese scharf hindurch. An den randlichen Teilen treten sowohl im Hangenden wie im Liegenden die bereits erwähnten biotitreichen Gesteine auf, die jedoch meist nach wenigen dm in die Granatamphibolite übergehen; kleinere Einschlüße bestehen ganz aus dem glimmerreichen Gestein.

GESTEINE DES KERNS

Das von Rosenbusch abgebildete Gestein ist ein graugrünes, massiges, feinkörniges Gestein, in dem zahlreiche bis 1 cm. große Individuen von sehr hellbräunlicher, von den anderen Gemengteilen "poikilitisch" durchbrochener Hornblende regellos so verteilt sind, daß sie in ihrer Mehrzahl zu einer auch durch schmale, grau gefärbte Lagen schwach angedeuteten Texturrichtung (=*s*-lagen im Sinne von *Sander*) subparallel angeordnet sind.

Granat bildet teils Körner, teils "atoll"-artige, auf der Innenseite oft kristallographisch scharf begrenzte Skelette (bis 0.7 mm. groß), die rahmenartig farblosen *Pyroxen* ($c:\gamma = 41°$, $2V_\gamma = 68°$) umschließen, sowohl Einzelstücke wie auch regellos verwachsene Körnergruppen. Auf der Aussenseite legt sich an den Granat ein 0.025 mm. breiter Saum von Pyroxenstengelchen mit Plagioklaskörnern ($n > 1.54$), hierum ein zweiter ebenso breiter Saum aus Pyroxenkörnern allein. Darauf folgt ein körniges Gemenge von Granat und Pyroxen. Die Hauptmasse bilden die großen *Hornblende*porphyroblasten, ohne kristallographische Umgrenzung ($c:\gamma = 15°$, $2V_\gamma = 85°$[1], $\gamma'_{(110)} = 1.657$; farblos durchsichtig, β ganz

[1] Eine ganz ähnliche Hornblende aus einem eklogitartigen Gestein (Geröll aus dem Elztal) zeigt deutlich Zonenbau (ohne scharfe Grenzen), wobei im gleichen Individuum $c:\gamma$ zwischen 16° und 22°, 2 V zwischen +87° und −72° schwanken.

schwach hellbräunlich), die die Granatskelette, bisweilen unter Entwickelung eines schmalen Reaktionssaumes von Pyroxen und Feldspat, und den Pyroxen umschließen. Pyroxen und Hornblende werden durch einen äußerst feinen grauen *Symplektit* von Pyroxen + Plagioklas verdrängt, der auch die in offenen Atollgranaten liegenden Pyroxene angreift und im Kontakt mit Granat Magnetitstaub führt. Der Symplektit gleicht völlig dem von Eskola beschriebenen. *Magnetit*, etwas *Magnetkies* und *Rutil* in Körnerform. *Apatit* fehlt völlig. Der Plagioklas-Pyroxensymplektit kann an Menge so zunehmen, daß er die Hauptmasse des Gesteins ausmacht. So entstehen hellgraue, sehr feinkörnige, fast dichte Gesteine, die vorherrschend aus subparallel angeordneten gestreckten *Symplektit*büscheln bestehen; darin liegen: *Granat*körner, mit Einschlüßen von *Rutil* und *Pyroxen*, umgeben von schmalen Säumen einer farblosen monoklinen *Hornblende*, die auch in einzelnen größeren Spiessen gemengt mit Plagioklaskörnern auftritt; ferner: *Pyroxen* farblos, in stark angefressenen Splittern, mit *c* parallel der Längsrichtung der Symplektitbüschel angeordnet. *Quarz* dringt, ähnlich wie im Eklogit selbst, von der Seite in Zungen zwischen die Symplektitlagen ein und zehrt sie auf unter Neubildung einer feinstengeligen farblosen Hornblende. Wenig *Erz* (Ilmenit und Leukoxen).

GRANATAMPHIBOLITE

Das dem Kern zunächst liegende Gestein ist dunkelgrün und besitzt deutlich ausgeprägte Paralleltextur.

Granat bildet gerundete Körner (bis 0.6 mm.); darin Rutileinschlüße.

Pyroxen, farblos in Skelettkristallen, z.T. für sich, z.T. mit ebenfalls skelettartig gebauter Hornblende gemengt.

Die *Hornblende* ist hellgrün mit α hellgelb, β bräunlichgrün, γ graugrün $\alpha < \beta > \gamma$, opt. negativ, teils in Skeletten, teils in schlanken Spiessen nach (110).

Plagioklas mit An_{40}–An_{46} mit wenig Zwillingsstreifung bildet ein feinkörniges Mosaik.

Biotit tiefbraun in Blättern (bis 0.9 mm.) und Gruppen vorwiegend parallel *s*: *Quarz* tritt in Einzelkörnern und Striemen (bis 1.6 mm.) parallel *s* auf. *Erz* ist sehr spärlich, Apatit fehlt.

Die Paralleltextur wird sowohl durch die Anordnung der Pyroxen- und Hornblendeskelette und des Biotits, wie auch durch die Quarzstriemen erzeugt. Die Struktur wird vor allem durch die Skelettkristalle beherrscht.

BIOTITAMPHIBOLITE

Mit weiterer Entfernung vom Kern verschwindet erst der Pyroxen, dann auch der Granat und an Stelle der Hornblende*skelette* treten kompakte, nur vereinzelt noch siebartig durchwachsene Säulen und Körner einer grünen *Hornblende* mit den gleichen Eigenschaften wie im Granatamphibolit (opt. negativ, c:γ 15–16°). Selten sind farblose Kerne. Zersetzungsprodukte Chlorit, Kalkspat. Die Menge des *Biotits* (rotbraun, mit pleochroitischen Höfen) nimmt zu, oft ist er stark chloritisiert. Die Zusammensetzung des *Plagioklases* wird z.T. kalkreicher; es wurde gefunden: An_{56-60}, An_{41-48}, An_{51-54}, vereinzelt auch An_{63}. Zonarer Bau ist häufig, z.T. invers. Der Plagioklas bildet auch hier stets ein feinkörniges Mosaik, wobei die Körner sich vielfach regellos diablastisch durchdringen. Das gleiche gilt für den in geringer Menge vorhandenen *Orthoklas*. Die Menge des *Quarzes* scheint zuzunehmen. Außer in Körnern und Striemen, die meist nur schwache Verzahnung und Felderung zeigen, tritt er auch in das Plagioklasmosaik ein. *Apatit* in wechselnder, meist geringer Menge. *Erze* selten (Pyrit, Magnetit, Magnetkies). *Titanit* ganz vereinzelt.

Das Gefüge wird von einer vorwiegend durch den Biotit und die Quarzstriemen bedingten Paralleltextur beherrscht, doch sind auch schmale Querbiotite gelegentlich vorhanden. Die Hornblende zeigt geringere Regelung. Die Struktur ist grano- bis diablastisch.

Ein Gestein mittlerer Zusammensetzung ergab auf dem Leitz'schen Integrationstisch folgende Volumprozente:

Hornblende	26.6
Biotit	25.7
Feldspat[2]	36.7
Quarz (Körner u. Striemen)	11.0

Bisweilen nimmt der Gehalt an Hornblende erheblich zu. Solche Gesteine sind dann meist auch gröber körnig und ähneln in ihrem Gefüge dem, was *Schalch* "verwischte Gabbrostruktur" nennt.

[2] Orthoklas und Plagioklas sind mengenmässig nicht sicher zu trennen.

Nahe dem hangenden Kontakt treten lokal Gesteine auf, in denen dem normalen, noch schwach granatführenden Amphibolit schmale andersartige Lagen parallel der Hauptschieferung eingeschaltet sind, und zwar:

1. Biotitplagioklasschiefer. Der *Plagioklas* bildet hier entweder mit Quarzkörnern in wesentlicher Menge durchsetztes feinkörniges Mosaik oder er besitzt die Form langer (bis 0.7 mm.) in die Schieferung eingepaßter xenomorpher Leisten, wobei die im Ganzen spärliche Albitstreifung teils parallel, teils quer, auch senkrecht zu dieser orientiert ist. Das Periklingesetz ist selten. Seine Zusammensetzung schwankt zonar (z.T. anscheinend invers) zwischen An_{48} und An_{70}. Der *Biotit* hat entweder die Form schmaler Blättchen oder bildet ausgezeichnete schwammartig lokere Skelettkristalle; in beiden Fällen parallel *s* Plagioklas-Einzelkörner und Mosaik durchsetzend, doch fehlen auch hier schmale Querbiotite nicht. *Quarz* kommt ebenso wie im Amphibolit in einzelnen größeren Körnern und schmalen Linsen vor. *Magnetkies* ist verbreitet.

Es ist interessant, daß dieses strukturell an Hornfelse erinnernde Gestein auch in rundlichen, einschlußartigen Partien im benachbarten Amphibolit auftritt, wobei sein *s* völlig unabhängig von dem des umgebenden Gesteins ist.

2. Helle Lagen aus vorherrschendem *Quarz* in durchschnittlich 2 × 0.4 mm. grossen, parallel *s* angeordneten schwach verzahnten Körnern und Körneraggregaten; *Disthen* in stark resorbierten und z.T. mit Reaktionssäumen von Spinell(?) und Pyroxen umgebenen Stücken, die gegen den Quarz durch einen schmalen Saum von Anreichem *Plagioklas* abgeschirmt sind, genau wie in den "Kalksilikatfelsen" der Fehren bei Neustadt.[3] Dazu kommen einzelne *Biotit*blättchen und *Magnetit*körner.

Auch hier treten rundliche Einschlüße von Biotitplagioklasgestein in willkürlicher Anordnung auf.

EINSCHLÜßE

Im zentralen Teil des Lagers treten, eng mit den Nebengestein verschweisst, bis faustgroße Partien eines hellgrauen quarzreichen Gesteins im Eklogit auf. An ihrer Zusammensetzung beteiligen

[3] O. H. Erdmannsdörffer, *Sitzungsber. Heidelberger Akad. d. Wiss.* (1936), Abh. 10.

sich: überwiegender *Quarz* in bis 1.2 mm. großen schwach verzahnten Körnern; *Plagioklas* von sehr wechselndem Aufbau: homogene Kristalle mit 26–35 An; zonare Individuen, mit z.T. normaler Schichtfolge (Kern $An_{36}\rightarrow$Rand An_{24}), invers ($An_{24}\rightarrow An_{30}$, $An_{27}\rightarrow An_{39}$, $An_{26}\rightarrow An_{35}$), alternierend ($An_{29}\rightarrow An_{37}\rightarrow An_{32}$, $An_{33}\rightarrow An_{23}\rightarrow An_{20}\rightarrow An_{33}$). In *einem* Individuum liegen oft mehrere "Kerne" und die Zonen verlaufen unregelmäßig und stossen an ± geraden Flächen aneinander ab. Auch Resorption An-reicher Kerne durch die Ab-reicheren Schalen ist nicht selten. *Biotit* rotbraun, meist völlig chloritisiert, z.T. eingeschlossen in spärlichen Körnern von *Granat;* reichlich *Apatit.*

Der Plagioklas hat teils angenäherte Leistenform nach (010), teils tritt er zu gestreckten Häufchen zusammen, die durch Quarz getrennt sind, sodaß eine schwache Paralleltextur entsteht.

KLUFTFÜLLUNGEN

Die S. 438–39 erwähnte N–S–Kluft wird von einem Gemenge von *Quarz* und bis über 6 mm. langen Leisten eines *Plagioklas* mit 15–20 An ausgefüllt.

Eine andere Kluft nahe dem Liegenden enthält: schöne homogene *Plagioklase* (Albit-Periklin-Baveno-gesetz), deren Zusammensetzung genau zu An_{53-55} bestimmt werden konnte. Dazu kommt viel *Quarz*, etwas *Biotit* und grüne *Hornblende*, die z.T. von den hellen Gemengteilen siebartig durchbrochen wird. Dazu etwas *Apatit.* Die Struktur ist aplitartig.

Im Eklogit sind schmale Klüfte mit feinfaseriger grüner *Hornblende* erfüllt.

NEBENGESTEIN

Der Biotitgneis des Liegenden zeigt durch die Biotitlagen stark ausgeprägtes *s.* Gemengteile sind: *Plagioklas*, z.T. fleckig zonar, mit $An_{28}\rightarrow An_{20}$, also normale Zonenfolge. *Biotit* stark pleochroitisch (mit Höfen), $\gamma - \alpha = 0.053$. *Quarz* schwach gefeldert; *Orthoklas* im ganzen stark zurücktretend, bildet einzelne größere Körner, die gerundete Leisten von Biotit und Plagioklas umschließen, gegen letztere durch Myrmekitsäume abgesetzt. *Sillimanit* bildet zarte Büschel im Feldspat, die in Zügen ± parallel *s* gelagert sind.

Die Biotittafeln bedingen das *s;* sie ziehen einzeln oder in Häuf-

chen ± parallel quer durch die Feldspäte und liegen auch *zwischen* den übrigen Gemengteilen, z.T. anscheinend in stark gelockerten Polygonalbögen angeordnet. Die farblosen Gemengteile umschließen das Ganze in äußerlich richtungslosem granoblastischen Gefüge.

Das aplitartige Gestein im direkten Hangenden ist feinkörnig (rund 0.75 mm.) und besteht aus: *Albit* An_5 (Max. $\perp a$ 15°, opt. +, α' und $\gamma' < 1.54$). *Orthoklas* meist homogen, selten etwas entmischt; *Biotit* in wenigen regellos zerstreuten Blättchen; *Granat* in einzelnen Körnern, z.T., auch in Atollform. *Sillimanit* z.T. mit Muskovit zusammen, in zarten Nadeln und Büscheln, quer durch die Feldspat- und Quarzkörner gehend. *Zirkon* in Spuren, Apatit fehlt.

Die Struktur ist rein granoblastisch, beherrscht durch die runden Grenzen und gegenseitiges Umschließen aller Gemengteile. Nur der Sillimanit bildet einzelne Züge von 1–2 mm. Breite quer durch das Gefüge der anderen Gemengteile.

CHEMISCHER BESTAND

Der Hornblendeeklogit aus der Mitte der Linse hat die folgende Zusammensetzung (Mittel aus 2 sehr gut übereinstimmenden Analysen von Fräulein M. Zumbusch):

SiO_2	49.84	si	100.7
TiO_2	0.67	al	16.5
Al_2O_3	13.87	fm	59.2
Cr_2O_3	0.12	c	20.4
Fe_2O_3	1.11	alk	3.9
FeO	8.21	k	0.02
MnO	0.12	mg	0.73
MgO	14.34	qz	−14.9
CaO	9.36		
Na_2O	1.96		
K_2O	0.07		
P_2O_5	0.00		
H_2O+	0.42		
H_2O-	0.14		
	100.24		
D	3.22		

Dieser Stoffbestand weist auf ein Ausgangsmaterial von gabbroider Zusammensetzung. Von den neuen Niggli'schen Mag-

mentypen[4] paßt am besten das eukritische der gabbroiden Magmen. Eine Reihe von Olivingabbros, Noriten u.a. sind ähnlich, doch ist bei ihnen das Verhältnis MgO > CaO in der Regel umgekehrt. Auf diese Beziehungen wie auch auf die chemische Zusammensetzung der umgebenden Amphibolite soll an anderer Stelle eingegangen werden.

GENETISCHES

Die Beschreibung zeigt, daß Eklogit im engeren Sinne des Wortes (Granat + Omphazit) nicht vorliegt; das Kerngestein enthält Hornblende als wesentlichen Gemengteil und als Abschluß einer "primären" Kristallisationsphase, die aber sicher nicht *magmatischer* Natur ist. Es liegt ein *Amphiboleklogit* vor.

Die zeitlich folgende Umwandlung zu Amphibolit hat das Gestein in diesem Zustand erfaßt. Sie bedeutet Anpassung an die im Gneis herrschenden Verhältnisse. Gneis und Eklogit sind nicht isofaziell, der Eklogitstoff und seine Ausprägung sind älter, der Eklogit als solcher ist mineralfaziell ein Relikt. Im Ganzen liegt also ein Vorgang *retrograder* Umwandlung vor: Eklogitfazies→Amphibolitfazies.[5] Die Reihenfolge und Reichweite der einzelnen Teilvorgänge geht aus dem nebenstehenden Schema hervor. Charakteristisch für den Gesamtverlauf ist insbesondere das Verschwinden des Granat, die Ablösung des "primären" Pyroxen durch den Symplektit und dessen Entwicklung zu Pyroxenskeletten, die dann gleichfalls verschwinden; der Ersatz der farblosen durch grüne Hornblende, erst in Skelettform, danach in Körnern und Säulchen und die nebenher laufende Entwicklung von Biotit, Plagioklas, und Quarz.

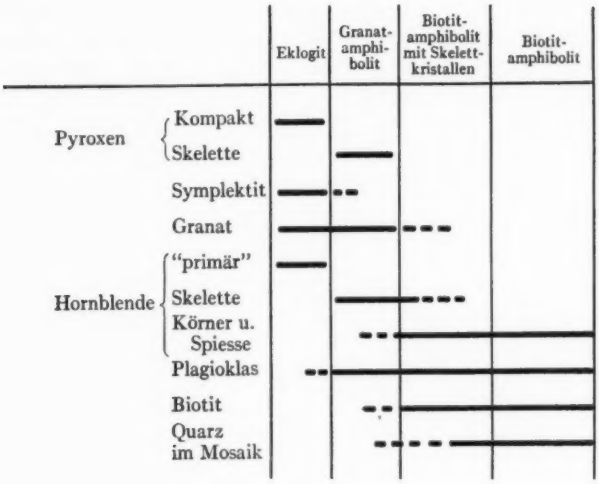
Das *Gefüge* der Amphibolite wird in weit höherem Masse als im Eklogit von einer Paralleltextur beherrscht, die, wohl sicher ursprünglich durch tektonische Deformation hervorgerufen, durch einen im wesentlichen statisch verlaufenden Endkristallisationsvorgang überdeckt wird, der jene abbildet. Auch die "verwischte Gabbrostruktur" (vergl. S. 441) ist, wenigstens in diesem Falle,

[4] *Schweiz. Min. Petr. Mitt.*, Band XXXVI (1926), S. 335.

[5] In anderen Schwarzwaldamphiboliten geht der retrograde Abbau bis zur Entwicklung einer Prasinitfazies zurück, die gelegentlich von einer Zeolithphase gefolgt wird.

kein Relikt praemetamorpher Zustände, sondern rein kristalloblastisch entstanden.

Auch im Gneis ist das Vorhandensein zweier Gefügephasen deutlich, eine frühere deformative, die aus der Anordnung der Glimmer- und Sillimanitzüge erkennbar ist, während seine Quarz-Feldspatanteile eine hiervon nahezu unabhängige Anordnung besitzen, die,



wenn auch sicher nicht ohne Regelung, doch anderer Art, und jedenfalls so zu Stande gekommen ist, daß die Spuren jener älteren Bewegungsperiode davon nicht wesentlich in Mitleidenschaft gezogen wurden. Ob diese Phasen zeitlich weiter auseinander liegen, oder zu *einem* Akt gehören, wird erst zu entscheiden sein, wenn die Genesis des gesamten Gneisgebietes klargestellt sein wird.

Die Zuordnung solcher Bewegungs- und Kristallisationsphasen zu den geologisch-zeitlich fixierten tektonischen Vorgängen im Gesamtaufbau des Schwarzwälder "Grundgebirges" ist zur Zeit ebenfalls noch nicht eindeutig möglich. Es steht fest, daß die Intrusionen der grossen varistischen Granitmassive die "Gneise"

und ihre "Einlagerungen" bereits als solche angetroffen haben; über deren Alter bestehen jedoch noch keine exakt begründeten Anschauungen: sie werden von verschiedenen Autoren teils als "sehr alt" angesehen, teils aber auch, soweit sie als "Orthogesteine" aufgefaßt werden, mit den Graniten in genetischen Zusammenhang gebracht, die selbst wieder in verschiedene zeitlich getrennte Phasen gegliedert werden können.

Der Schwarzwald war das erste Gneisgebiet, in dem vor nunmehr 40 Jahren eine geologische Durchforschung unter Zugrundelegung vorwiegend *genetischer* Gesichtspunkte unternommen wurde, die sich in erster Linie an die Namen "Sauer" und "Rosenbusch" knüpfen. Dem damaligen Stand der Erkenntnisse entsprechend, waren Dynamometamorphose, Kontaktmetamorphose, Gliederung in Abkömmlinge eruptiven oder sedimentären Ausgangsmaterials die richtungsweisenden theoretischen Leitlinien, zu denen später noch die Injektionsmetamorphose hinzukam (Philipp, Niggli u.a.).

Heute stehen wir vor der Aufgabe, zu prüfen, wieweit neben oder statt der genannten Faktoren die in zahlreichen anderen Gebieten gewonnenen und mit Erfolg angewandten Anschauungen über Anatexis, Migmatitbildung, Metasomatose, Gefügeregelung, Polymetamorphismus u.a. auf unser Gebiet zu übertragen sind, in dem einige von ihnen, wie wir jetzt schon wissen, ihre Spuren hinterlassen haben. Die "Gneisformation" des Schwarzwaldes ist so rätselreich wie je. Ehe aber eine Synthese möglich sein wird, bedarf es noch zahlreicher Einzelforschungen. Solche Arbeiten sind im Heidelberger Mineralogisch-Petrographischen Institut im Gange und dieser Aufsatz ist ein kleiner Teilausschnitt aus ihnen.

ON THE ESBOITIC CRYSTALLIZATION OF ORBICULAR ROCKS

PENTTI ESKOLA
Mineralogical and Geological Institute, University of Helsinki

INTRODUCTION

In his *Descriptive Petrography* Albert Johannsen has given an elucidative description of orbicular rocks. It was because of his interest in these rocks that I was inspired to offer the present contribution to his jubilee volume. The reader is referred to Johannsen's textbook for references to the literature and for much further information.

Another volume that the reader of the present paper should have at hand is J. J. Sederholm's memoir, "On Orbicular Granites, Spotted and Nodular Granites, etc. and on the Rapakivi Texture."[1] In this memoir Sederholm gives a detailed description, with numerous illustrations and chemical analyses, of four Finnish orbicular granites, presents additional observations and illustrations of the two orbicular granites of Virvik and Kangasniemi earlier described by Benjamin Frosterus, and cites extensively my earlier short description of the orbicular diorite of Pöytyä. He includes, furthermore, a detailed discussion of the theories concerning the genesis of orbicular rocks and presents his own conclusions. As space does not permit a general discussion in this paper, I refer to the work of Sederholm; also, the bibliography of orbicular rocks which is fairly complete up to 1928 in his pamphlet.

There is one point in Sederholm's conclusions on which I wish to lay special stress, and it is this:

> The present rocks are so rare in occurrence that it seems probable that they may also possess an exceptional composition. A chemical investigation shows this to be true. They show characters that are not, or at least very seldom, found in any other rocks. . . . . They are high in Al_2O_3, Na_2O, and CaO, while the contents of K_2O vary, being sometimes very low, and commonly much higher in the matrix and the surrounding rock than in the spheroids.[2]

[1] *Bull. Comm. Géol. Finl.*, No. 83 (1928). [2] *Ibid.*, p. 72.

Sederholm, therefore, proposes to "designate rocks of this magma type, i.e. oligoclasitic diorites, as *esboites*, after the rock from Esbo."

This type of rocks really seems to deserve a name of its own. It does not seem appropriate, however, to speak of an "esboitic magma type," as it is clear in many cases that rocks of oligoclasitic composition never have existed as magmas possessing a composition at all like that of the present rocks. The term "esboite" as used in this paper means a rock in which dominant plagioclase is oligoclase or andesine, and "the esboitic crystallization of orbicular rocks" is the process, so far very mysterious indeed, by which the orbicules have attained this composition.

This is almost the only one among Sederholm's conclusions in which I can agree with him. I must note this, as his conclusions cannot be discussed any further in this paper. The reader may find out by comparison the difference in the manner of approaching the problem. My conclusions are, nevertheless, for a large part based upon Sederholm's masterly observations. It soon appeared, however, that more chemical data were necessary to reach an idea about the genesis of the esboitic orbicules. Moreover, four new finds of orbicular rocks have been made in Finland during the last decade, and these will be briefly described. Two of these were subjected to chemical analyses, as well as several other orbicular rocks.

Most of the orbicular rocks are esboitic in character. A well-known exception to this rule is the orbicular "diorite" from Santa Lucia di Tallano, Corsica, the feldspar of which is bytownite, but which in all structural respects behaves like the esboites. A few notes on this classical rock are therefore included. I am also including a picture and a few words about an orbicular rock of esboitic character found near the river Kurumkan in the Bargousin Valley, Transbaikalia, by Professor K. J. Viskont, now of the All-Union Scientific Research Institute of Economic Mineralogy in Moscow. He found boulders of this rock during our expedition to Transbaikalia in 1914. I am much indebted to Professor Viskont for his kindness in giving me his photographs and thin sections for free use.

There are several other kinds of nodular rocks, sometimes called orbicular, which are not esboitic and which, therefore, are not considered in the present paper, such as the "pudding-granite" of

Craftsbury, Vermont,[3] in which the nodules are mainly composed of biotite; or the orbicular gabbros of Romsaas, Dehesa,[4] and Davie County,[5] in which the orbicules seem chiefly to be due to the radiating growth of pyroxene; or the quartz-sillimanite-bearing nodular granites;[6] or the remarkable cordierite-bearing orbicular rock of Minedera-yama, Japan.[7]

CORSICA

Slabs of "orbicular diorite" from Santa Lucia di Tallano, Corsica, are valued show specimens in most petrographical museums. Pictures and descriptions of the rock may be found in handbooks and current literature. Analyses 1 and 2 (Table 1) were made of a specimen kept in our museum (Fig. 1*a*).

The orbicules are very uniform in structure and size. In most of them there is a small nonoriented core which is medium-grained and mineralogically similar to the matrix, but contains less of the colorless amphibole described below. Around this nucleus the minerals are arranged in regular zones. The innermost zone starts from the nucleus without any sharp boundary by decrease of the amphibole, and the plagioclase assumes a radiating arrangement. The next zone is narrow and consists only of green and colorless amphibole prisms arranged radially. Around this is a broad plagioclase zone in which bytownite lamellae radiate outward. They are very thin in proportion to their length, the axis *a*, or the zone [100] being the direction of elongation. In tangential thin sections most individuals show traces of both cleavages, *P* and *M*, while in sections across the orbicules many of the long needles show twinning lamellae of the albite type in the longitudinal direction. One or two narrow dark zones near the outer margin are composed of minute hornblende prisms, and most of the long plagioclase needles penetrate these hornblende

[3] A. Johannsen, *A Descriptive Petrography of the Igneous Rocks* (Chicago: University of Chicago Press, 1932), Vol. II, p. 352.

[4] Sederholm, *op. cit.*, p. 71.

[5] Thomas L. Watson, "Orbicular Gabbrodiorite from Davie County, North Carolina," *Jour. Geol.*, Vol. XII (1904), p. 294.

[6] Sederholm, *op. cit.*, p. 80.

[7] B. Yoshiki, "Petrographic Notes on the Orbicular Rock from Minedera-yama," *Proc. Imp. Acad.*, Vol. IX, No. 10 (1933); Y. Kawano, "Chemical Studies on the Orbicular Rock from Minedera-yama," *Proc. Imp. Acad.*, Vol. IX, No. 10 (1933).

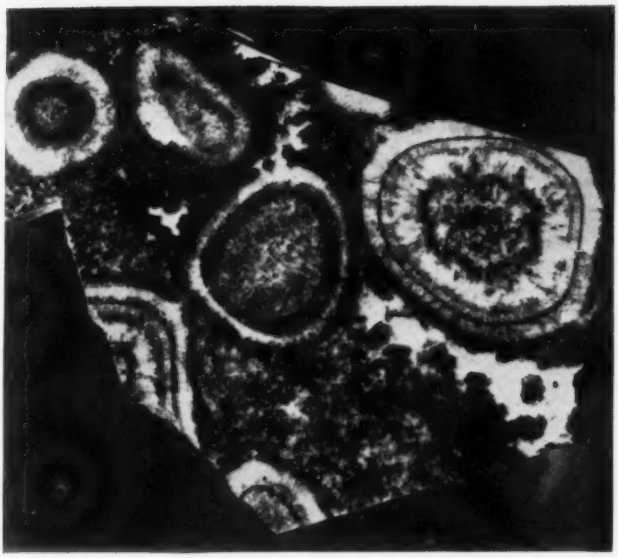


FIG. 1*a*.—Santa Lucia di Tallano, Corsica. $\frac{5}{8}$ natural size

FIG. 1*b*.—Pöytyä. Two of the orbicules in the middle show corroded embayments at their margins. The corroding material, or "cancer," is red-pigmented pegmatitic plagioclase with quartz crystals ending in drusy cavities. $\frac{3}{4}$ natural size.

zones, while others end sharply against the hornblende prisms. The latter are frequently arranged concentrically with their (100)-planes in tangential positions.

The hornblende in the orbicules as well as in the matrix is pale green, and certain parts of the crystals are colorless. They show very small extinction angles, and in many prisms near the (010)- position straight extinction was observed. This is a ferromagnesian amphibole, anthophyllite, or cummingtonite, as verified by the analyses.

The Corsica rock shows much heterogeneity in the matrix and contains portions which are very coarse-grained and mainly composed of plagioclase. The rock is often spoken of as diorite, but, as appears from the analyses, it should rather be called gabbro or hornblende-gabbro. Analyses 1 and 2 give an idea of the composition of orbicule and matrix. The plagioclase in the center as well as the shell of the orbicule gave, by the immersion method, $\alpha' = 1.570$, $\gamma' = 1.579$, corresponding to the composition An_{88}, while that of the matrix gave $\alpha' = 1.564$, $\gamma' = 1.572$, and should be An_{75}.

The mode was calculated from many analyses during the present work, but the results led to the conclusion that the percentage values are often uncertain up to several per cent and give an illusory idea of the accuracy. The uncertainty is due partly to possible errors in the analyses and partly to the great variability in the composition of the mafic minerals, amphibole, and biotite. The modes will not, therefore, be published, except that of the Corsica matrix given below. It was calculated using the analysis of hornblende from quartz-diorite, Tioga Road,[8] and fits well with the observed mineral composition. About half of the amphibole is cummingtonite; the green hornblende, from the matrix as well as from the orbicule, gave in cleavage splinters $\alpha' = 1.648$, $\gamma' = 1.661$. The mode of matrix, not considering minor epidote, chlorite, and apatite, is:

Bytownite			Hornblende	Cummingtonite	Sum
An	Ab	Or			
50.0	14.8	2.0	16.7	15.3	98.8

PÖYTYÄ

A boulder of orbicular rock was found by me in 1917 at the side of the highway seven kilometers from the village of Riihikoski on

[8] H. Rosenbusch, *Elemente der Gesteinslehre* (1901), p. 140, Analysis 11.

the way to Yläne, in the parish of Pöytyä in southwest Finland.[9] In 1935 I had about half of the boulder quarried off and sawed into

TABLE 1

ANALYSES OF THE ORBICULAR ROCKS FROM CORSICA, PÖYTYÄ, AND LAUKAA

	1	2	3	4	5	6	7	8
SiO_2	46.64	48.60	54.73	49.29	58.81	49.08	51.60	71.72
Al_2O_3	29.06	22.96	25.30	19.74	19.33	12.82	6.79	12.89
Fe_2O_3	1.36	2.12	1.44	2.80	2.08	3.36	3.04	1.36
FeO	1.94	4.43	1.44	6.19	4.42	15.98	20.30	3.17
MnO	0.04	0.08	0.04	0.15	0.17	0.40	0.82	0.09
MgO	2.57	5.61	0.54	5.40	1.38	5.40	8.87	0.82
CaO	15.12	12.05	8.90	9.26	5.73	4.42	4.41	1.97
Na_2O	1.67	1.88	5.34	3.82	5.80	2.28	0.99	3.64
K_2O	0.27	0.44	0.81	0.82	1.36	3.45	0.68	2.65
TiO_2	0.12	0.40	0.17	0.86	0.20	1.04	0.21	0.42
P_2O_5	.....	.....	.....	tr.	tr.	tr.	.....	.....
H_2O+	1.81	1.93	0.77	1.56	0.72	1.63	2.23	0.98
H_2O-	0.07	0.03	0.11	0.10	0.16	0.17	0.17	0.08
Total	100.67	100.53	99.59	99.99	100.16	100.03	100.11	99.79
				NORMS				
q	.....	0.46	0.96	.....	3.73	.....	6.16	32.95
or	1.62	2.62	4.80	4.86	8.04	20.43	4.02	15.69
ab	14.15	15.94	45.29	32.24	49.18	19.35	8.42	30.88
an	70.98	53.00	42.64	34.33	22.65	14.50	12.05	9.79
cor	.....	.....	.....	.....	.....	.....	.....	0.43
wo	1.75	2.89	0.68	4.89	2.44	3.11	4.12	.....
fs	1.74	5.88	1.26	1.44	6.39	12.32	36.00	4.19
en	4.67	14.00	1.35	1.36	3.44	6.47	22.14	2.04
fa	0.45	.....	.....	4.79	.....	10.28	.....	.....
fo	1.19	.....	.....	8.40	.....	4.87	.....	.....
mt	1.97	3.08	2.08	4.06	3.01	4.87	4.40	1.97
il	0.23	1.16	0.32	1.62	0.38	1.98	0.40	0.79

1. Orbicule. Santa Lucia di Tallano, Corsica.
2. Matrix. Santa Lucia di Tallano, Corsica.
3. Orbicule. Pöytyä, Finland.
4. Matrix. Pöytyä, Finland.
5. Feldspathic nucleus of orbicule. Laukaa, Finland.
6. Shell of orbicule. Laukaa, Finland.
7. Hornblendic nucleus of orbicule. Laukaa, Finland.
8. Matrix. Laukaa, Finland.

big slabs, a dozen of which were polished on one side (Fig. 2). The structure is better seen in pictures made on a larger scale (Fig. 1*b*).

[9] Cf. Sederholm, *op. cit.*, p. 45.

The rock is composed of lighter orbicules, lying densely crowded in a dioritic hornblende-plagioclase matrix, which is coarsely granular but not uniform, containing in some parts only a little and in other parts much plagioclase, partly as big crystals. According to determinations made on five big slabs, the orbicules make up 66.7 per cent of the volume of the rock.

No pictures can reproduce the beauty of the rock, due to the delicate coloring seen in reality on the polished surfaces. Except for dark dioritic nuclei in some of the orbicules, their inner parts are light gray, but stained with pink spots, giving a total effect of light red. The aggregates of the coarse plagioclase crystals in the matrix are often likewise pink-pigmented. Around the lighter radiating central parts the orbicules possess a shell, about 1 cm. thick, which is dark-bluish gray in tint and contains minute disseminated grains of magnetite. They are more densely crowded in two or three zones within the blue mantle. We here meet with a peculiarity common in many orbicular rocks, viz., that definite zones in different orbicules possess an analogous position in the structure. Individual differences, which may be very great, are due to the different development of the zones or even a total absence of some of them.

The light-red inner parts of the orbicules contain, besides plagioclase, sparse anhedral crystals of hornblende, a few millimeters in diameter, visible in the pictures. In many orbicules they are crowded in the center, giving the appearance of fragments of similar dioritic rock as the matrix (Fig. 2). A few of these nuclei are very big, dark in color from much hornblende, and more fine-grained than the matrix. These inclusions give the impression of true fragments, the growth of the orbicules being, however, the same as in the other orbicules though with a reduced breadth of the zones. These fragments seem to be primary inclusions in the diorite, while the more common dioritic nuclei seem to be portions of the diorite forming the matrix.

The majority of the bigger plagioclase crystals grown around the central nuclei or directly from the central point are radially elongated, exhibiting a negative character of elongation and twinning lamellae of the albite type in the same direction. For andesine this means that the elongation is parallel to axis *a*. The crystals thus

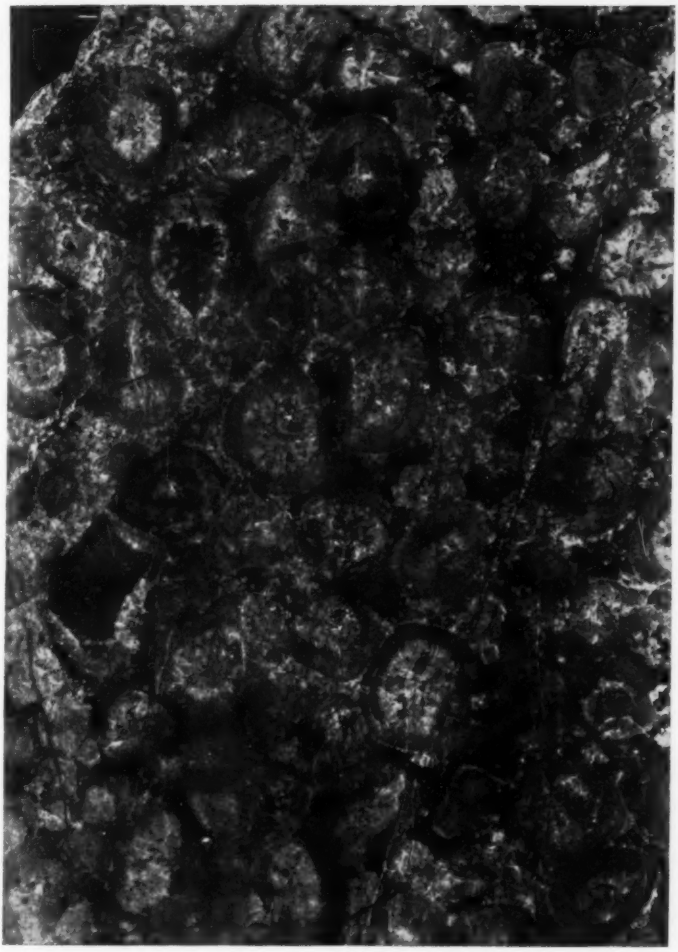


FIG. 2.—Pöytyä. One orbicule has a dioritic nucleus, similar to the groundmass; and another, in the lower half of the left-hand side, is an "embryonal" orbicule with a nucleus of fine-grained dark diorite. ½ natural size.

arranged are the biggest ones and make up the greater part of this coarsely crystalline central zone, while the crystals arranged otherwise are equidimensional, small, and fewer in number. Outward the amount of the big elongated crystals decreases and the bluish-gray outer zone assumes a granoblastic structure, but even here the individuals, arranged with their *a*-axes radially, are elongated in this direction (Fig. 9*a*).

The hornblende in the matrix, as well as in the orbicules, is of the common green type of a medium intensity of colors and showing $\gamma \wedge c = 16°$ and $\alpha' = 1.670$, $\gamma' = 1.684$. Titanite and apatite are sparse accessories. The hornblende has been slightly altered into epidote and light-green chlorite. In certain spots these low-temperature minerals are more abundant. These spots are very marked megascopically, their plagioclase being red-pigmented; and quartz, which is absent elsewhere in this rock, is a prominent constituent in xenomorphic individuals which fill up the spaces between euhedral feldspar and hornblende crystals, sometimes in the manner of the filling mass of drusy cavities. These red spots often have corroded parts of the outer zones of orbicules protruding into them like a destructive disease, a *cancer*. Such *cancers*, dark in the photographs, may be seen in Figure 1*b*.

The rock is traversed by numerous joints showing on polished surfaces as light streaks. The newly crystallized mineral by which the fissures have been healed is prehnite. As may be seen in Figure 1*b* and Figure 2, the fissure veins appear only in the orbicules and in the plagioclase crystals of the groundmass, while the fissures seem to have healed without any scars in the hornblende-rich matrix.

Several determinations of the refractive indices of the plagioclase gave for the orbicule $\gamma' = 1.557$, $\alpha' = 1.549$; and for the matrix $\gamma' = 1.556$, $\alpha' = 1.548$. Extinction angles in sections at right angles to *PM* vary somewhat. In different zones of the orbicules 28° was frequently found, in the matrix 26°, but here the crystals are zoned, and narrow border zones of the same crystals may show angles as small as 20° and even 15°. In a *cancer* an angle of 22° was measured in the zone perpendicular to *PM*. Thus, the composition seems to be rather constant, about An_{40} or An_{45} within the orbicule, and very little more albitic in the matrix. The normative plagioclase,

as calculated from Analyses 3 and 4, shows somewhat higher An percentages due to the fact that the hornblende is high in alumina, which enters into the normative plagioclase.

LAUKAA

In 1933 Mr. Erkki Vaheri brought to our Institute three boulders of orbicular rock which he had found on a morainic hill named Multamäki, near Lake Peurujärvi in the parish of Laukaa, north of the town Jyväskylä in central Finland. A fourth boulder is still in the possession of Mr. Vaheri, and a fifth, a very big one, is, according to him, lying in the yard of the farm Vanha-Viikki on Multamäki. The rock has not been found in place.

Of the three boulders given to our Institute, one was made into four polished slabs. It shows ellipsoidal, spheroidal, and more irregular rounded orbicules (Fig. 3) embedded in a pegmatitic matrix of white plagioclase, reddish microcline, smoky quartz, and large scales (up to 1.5 cm.) of black biotite. Most of the nuclei consist of hornblende-oligoclase-diorite, which is either even- and medium-grained, massive or gneissoid, or coarse porphyritic with phenocrysts of plagioclase. Still other nuclei are medium-grained and granitic in appearance, as seen in the biggest orbicule of Figure 3. Still a few other orbicules have nuclei of only coarsely crystalline plagioclase, sometimes a single crystal, in graphic intergrowth with quartz. The nuclei are often surrounded by a narrow hornblende-rich zone, after which follows another narrow light-colored zone of plagioclase and hornblende, enclosed by a thick outer black zone, rich in hornblende and biotite.

The other two smaller boulders (Fig. 4*a*) have two kinds of orbicules, some containing nuclei of coarsely crystalline oligoclase with quartz, hornblende, and biotite, surrounded by a dark mantle of biotite, hornblende, quartz, and plagioclase; and others containing nuclei of amphibole (mainly cummingtonite) with some plagioclase and biotite. The pegmatitic matrix is similar in all three boulders investigated. They have probably been derived from the same unknown occurrence.

The amphibole-rich nucleus (Analysis 7) consists of a rather coarsely crystalline mass of amphibole and plagioclase. The amphi-

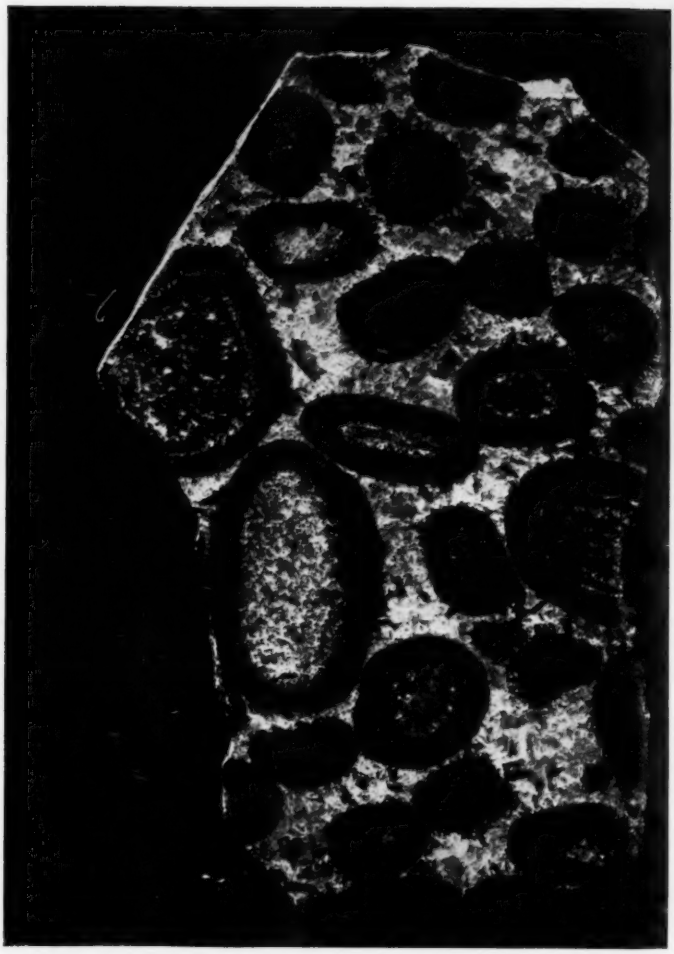


FIG. 3.—Laukaa. The nuclei consist of various rocks. A small orbicule in the upper half has a pegmatitic nucleus. $\frac{5}{11}$ natural size.

FIG. 4*a*.—Laukaa. Various nuclei, some pegmatitic, others hornblendic, as that of the big double orbicule in the right-hand side. ⅓ natural size.

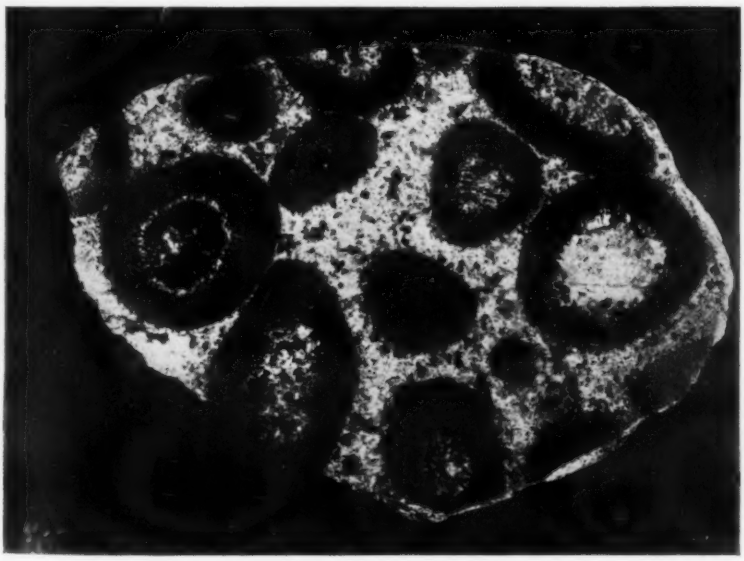


FIG. 4*b*.—Mäntyharju. Various nuclei: dark hornblendic, gray granular quartz-dioritic, pegmatitic with graphic plagioclase (right-hand side). ⅓ natural size.

bole grains are in their inner parts colorless in thin section, but near their margins they pass over into common green hornblende. The colorless amphibole shows $c \wedge \gamma = 19°$ and a positive optical character with a large axial angle, while the green hornblende is negative with a much smaller axial angle. Thus, the colorless variety is cummingtonite, as was also shown by the analysis. The plagioclase is about An_{27}, showing in section perpendicular to *PM* extinction angles of 16°, and $\gamma' = 1.550$ and $\alpha' = 1.542$. Still, there is some quartz filling up interstices between the plagioclase grains.

The cummingtonite-rich nucleus is bounded by a hardly perceptible zone of plagioclase and green hornblende, which rapidly passes over into the dark shell whose mineral composition is similar to the shell (Analysis 6) around the plagioclase nucleus. Both hornblende and biotite are well oriented, most hornblende prisms lying with (100) and most biotite prisms with (001) tangentially in the orbicule.

The matrix (Analysis 8) is pegmatitic and nonhomogeneous, showing individuals of quartz and feldspars measuring even a few centimeters in diameter. Plagioclase showed $\alpha' = 1.540$, $\gamma' = 1.548$, and maximum extinction angles in the zone perpendicular to (010) of 7°, corresponding to the composition An_{24}. In larger idiomorphic grains which are zoned, values up to $\gamma' = 1.550$ and maximum extinction angles of 10° were found.

All the different kinds of nuclei, excepting those of plagioclase with quartz, are apparently foreign inclusions around which similar mantles of oligoclase and hornblende have grown. According to the definition, this rock is not esboitic; still, it is noteworthy that the plagioclase from the feldspathic and hornblendic nuclei, from the dark mantle, and from the matrix invariably showed the same refractive indices and extinction angles as mentioned above. Biotite always showed $\gamma \cong 1.659$, and cleavage splinters of hornblende $\gamma' \cong 1.690$, $\alpha' \cong 1.671$, no matter from what part of the rock the sample was taken.

MÄNTYHARJU

In 1935 Dr. H. Väyrynen was informed about a boulder of orbicular rock found by a local schoolteacher in the village of Nurmaa, parish of Mäntyharju, southern central Finland. He visited the lo-

cality and obtained the boulder, which had been lying upon stoneless sand deposits. For the present investigation this small boulder was sawed and polished (Fig. 4*b*).

The Mäntyharju rock very much resembles the Laukaa rock. One megascopic difference is that the matrix of the Mäntyharju rock is less coarse-grained and its characteristic black biotite scales only from 0.5 to 0.8 cm. in width. Some of the nuclei of the orbicules are similar to the matrix, consisting chiefly of plagioclase, biotite, and quartz; others are dark and rich in hornblende; while some are pegmatitic with much quartz, partly in graphic intergrowth with the feldspar.

Nuclei similar to the matrix in structure show idiomorphic plagioclase grains with $\alpha' = 1.542$, $\gamma' = 1.550$, and maximum extinction angles of 13° corresponding to An_{27} or An_{29}, the same in the center as at the margin of the orbicule. Zoning is only slightly developed. The matrix has quite the same structure (Fig. 9*c*), but the plagioclase is more albitic ($\alpha' = 1.541$; $\gamma' = 1.548$; maximum extinction angle 8.5°), An_{24} or An_{25}. This plagioclase is distinctly zoned, the extinction angles decreasing a few degrees toward the margin of the grain. In the dark mantle the subordinate plagioclase shows the same characters as in the matrix. The amphibole is partly dark-green hornblende and partly colorless cummingtonite.

The arrangement of the minerals in the mantle of the orbicule is very interesting, resembling that of the Laukaa mantles, but also that of the hornblende-rich mantle of the Kortfors rock. The plagioclase shows a radiating arrangement (Fig. 9*b*), as does also the hornblende as far as the form is concerned; but, curiously enough, its elongation is parallel to the shorter diagonal, and the crystals are actually arranged concentrically with their (100)-directions in tangential positions in the spheroid, just as most of the biotite crystals have their (001)-planes in tangential positions, but are elongated in the prismatic zone. A possible explanation to this strange kind of schistosity will be given later.

HANKASALMI

The orbicular rock from Hankasalmi, central Finland, has been described and well illustrated by Sederholm. I reproduce in Figure

5*a* a photograph of half of the orbicule, the other symmetrical half of which was used for investigation. The central nucleus consists of a group of plagioclase with much microcline and some quartz. An analysis of the nucleus gave 4.46 per cent Na_2O and 5.05 per cent K_2O. Sederholm[10] found a nucleus consisting chiefly of microcline.

Different parts of the rock were analyzed, and the results were used in the diagram, Figure 11, but they will not be published in the present paper. In the concluding chapter some features of this rock, important for the problem of genesis, will be mentioned and discussed. Most important, perhaps, is its migmatitic matrix containing remains of a quartz-dioritic rock similar to the Mäntyharju matrix. In its best-preserved portions, its plagioclase has the same composition as that of the nucleus and the zones of the orbicule, namely, An_{28}. Henceforth, we shall call this kind of matrix the *primary matrix*.

KANGASNIEMI

The classical orbicular granite from Kangasniemi in central Finland was taken up for renewed investigation because the complexity of its character seemed to require some closer observations and more complete analyses than those contained in the memoir of Frosterus.[11] Figure 5*b* shows in the center an orbicule that was regarded by Frosterus as typical. New analyses have been made of the central fragment and the three inner zones from another orbicule of this type, and of the matrix (Table 2).

Microscopically, the central gneiss (Analysis 9) shows a schistose structure, owing to a partial parallel arrangement of the biotite, which is the constituent second in abundance after the plagioclase. Pale-green hornblende is the third constituent. No microcline is present. At the outer boundary of the fragment a few big non-oriented crystals of biotite and hornblende occur enclosed in the coarse radiating plagioclase, which, with interstitial quartz, forms the first zone (Analysis 10). It contains also some biotite and a few inclusions of microcline. This lamellar inner zone grades over into the second fine-grained granoblastic plagioclase zone with very little microcline and some biotite (Analysis 11), showing neither

[10] *Op. cit.*

[11] *Bull. Comm. Géol. Finl.*, No. 4 (1896).

FIG. 5*a*.—Orbicule of the Hankasalmi rock. Pegmatitic matrix encloses detached fragments of the dark shell of the orbicule. $\frac{3}{4}$ natural size.

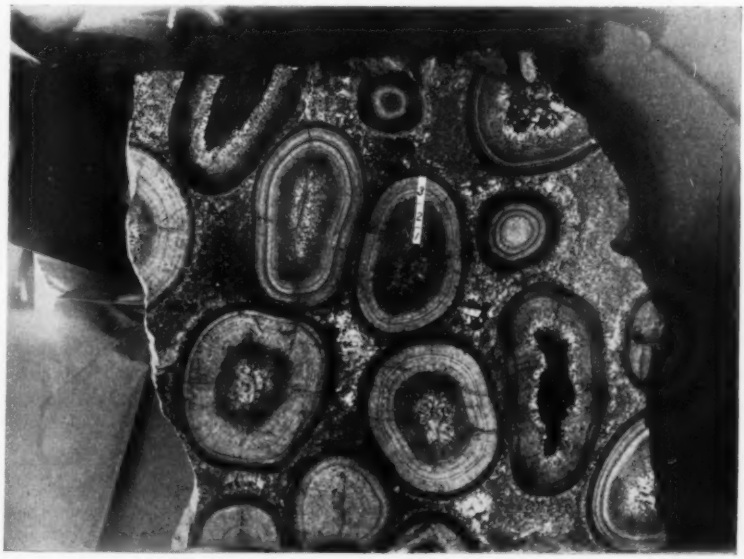


FIG. 5*b*.—Kangasniemi. In the middle a typical orbicule with a central gneiss fragment and (*1*) coarse-grained radiating plagioclase zone; (*2*) fine-grained granoblastic plagioclase zone; (*3*) microcline zone. Around this a dark shell of granoblastic plagioclase. In two ellipsoidal orbicules with big central gneiss fragments no microcline zone occurs; in the spheroidal orbicule in the upper right-hand corner with a quartz-dioritic nucleus the microcline zone is represented by two narrow bands only. $\frac{1}{6}$ natural size.

lattice nor form orientation. This zone, again, is sharply bounded by the third zone, which consists of lamellar microcline and quartz

TABLE 2

ANALYSES OF THE ORBICULAR ROCKS FROM KANGASNIEMI AND KORTFORS

	9	10	11	12	13	14	15	16	17
SiO_2	52.73	63.89	70.22	75.20	74.54	61.11	57.53	53.41	73.04
Al_2O_3	18.62	20.44	16.19	13.14	12.59	17.37	19.53	20.46	13.19
Fe_2O_3	3.84	0.80	0.64	.....	0.80	1.45	1.53	2.90	0.65
FeO	6.33	1.30	1.44	0.58	1.44	5.00	5.86	8.43	1.63
MnO	0.12	0.04	0.03	0.02	0.04	0.10	0.10	0.10	0.04
MgO	3.66	0.39	0.49	0.10	0.47	1.05	0.45	0.43	0.14
CaO	4.24	5.12	4.50	0.62	1.06	4.78	5.31	4.24	1.39
Na_2O	4.73	5.21	4.18	2.13	2.68	4.74	5.68	6.04	3.36
K_2O	3.93	1.24	1.76	7.57	5.86	3.29	1.81	1.69	6.39
TiO_2	0.90	0.20	0.35	0.10	0.21	0.85	1.90	1.52	0.30
P_2O_5	.....	tr.	.....	.....	.....	0.01	.....	.....	.....
H_2O+	1.12	0.58	0.48	0.22	0.39	0.42	0.48	0.62	0.19
H_2O-	0.36	0.14	.....	0.06	0.09	0.02	0.04	0.06	0.05
Total	100.58	99.35	100.28	99.74	100.17	100.26*	100.22	99.90	100.37

NORMS

q	16.45	28.42	31.79	32.88	7.59	3.24	.....	25.70
or	7.37	10.44	44.88	34.72	19.48	10.72	9.99	37.85
ab	44.18	35.45	18.04	22.72	40.19	48.18	51.23	28.77
an	25.46	20.16	3.07	4.96	16.69	22.67	21.08	1.92
cor	1.17	.....	0.30	.....	.....	.....	1.05	.....
wo	.....	0.92	.....	0.13	2.97	1.56	.....	2.08
fs	1.48	1.58	0.95	1.72	6.45	6.38	8.16	1.97
en	0.98	1.22	0.25	1.18	2.62	1.13	0.76	0.35
mt	1.16	0.93	.....	1.16	2.11	2.22	4.21	0.95
il	0.38	0.67	0.18	0.40	1.61†	3.60	2.89	0.56

* Includes S 0.07.

† Includes pyr 0.13.

9. Nucleus, gneiss fragment. Kangasniemi, Finland.
10. First zone (coarse-grained plagioclase zone). Kangasniemi, Finland.
11. Second zone (fine-grained plagioclase zone). Kangasniemi, Finland.
12. Third zone (microcline zone). Kangasniemi, Finland.
13. Matrix. Kangasniemi, Finland.
14. Pegmatitic nucleus of orbicule. Kortfors, Sweden.
15. Inner zone of orbicule. Kortfors, Sweden.
16. Shell of orbicule. Kortfors, Sweden.
17. Matrix. Kortfors, Sweden.

(Analysis 12) with very little biotite and no plagioclase excepting fine perthite strings. The radiating microcline lamellae broaden out-

ward, and quartz forms elongated but irregular inclusions, which show no lattice orientation noticeable by means of a gypsum plate. In this orbicule the microcline zone is divided into two spheres by a thin plagioclase zone, and the outer microcline zone is again sharply bounded by the plagioclase shell, which is darkest in color and finest in grain of all zones. In structure it is granoblastic and nonoriented and contains some biotite and some recurrent narrow microcline zones. An alkali determination of the outermost zone by Miss Ståhlberg gave 3.83 per cent Na_2O and 2.96 per cent K_2O. The composition of the plagioclase is An_{28-30} (the extinction angle in section perpendicular to $PM = 12°$, $\alpha' = 1.544$, $\gamma' = 1.551$), being the same as in the fragment and all the zones.

Analysis 13 shows the composition of the matrix, which is normal granitic, as is its structure. Its plagioclase also is more albitic than that of the orbicule. Thus, there is a marked hiatus between the orbicule and the matrix. It is important to note, however, that the matrix is migmatitic and not the same as it was originally when the orbicules were enclosed in it. Figure 5*b* shows well some better preserved, more fine-grained and dark-colored portions of the matrix, the most coarse-grained pegmatitic portions with drusy cavities being situated, as a rule, midway between the orbicules. Microscopically, the best preserved portion shows a medium-grained granitoid structure and a fair amount of biotite among idiomorphic plagioclase (An_{23}) with microcline and quartz.

Figure 5*b* shows, in its upper right-hand corner, an orbicule having a central nucleus of coarsely granitic structure. Actually, this rock is biotite-quartz-diorite, devoid of microcline excepting antiperthitic inclusions in the plagioclase, which is the most abundant constituent. The latter mineral forms idiomorphic phenocryst-like crystals with faint zoning. In its center a big crystal cut perpendicular to *PM* showed extinction angles of 14°; at the margins the angles are a few degrees smaller. Biotite is the other chief constituent, while xenomorphic quartz is third in amount. The innermost zone of the orbicule around the quartz-dioritic nucleus is coarsely lamellar, as usual, and grades over into the fine granoblastic zone, in which there are two narrow microcline zones, each only 1 or 2 mm. broad. Elsewhere there is no microcline in the concentric zones, and

the plagioclase possesses in all the zones the same composition, approximately An_{29}, being the same as that of the nucleus.

Another orbicule, seen in the upper left-hand corner of Figure 5*b*, has a long fragment of dark hornblende-gneiss as the central nucleus, surrounded only by a single plagioclase shell, the grain of which diminishes outward in the usual way, and with no trace of the microcline zone at all.

To find an answer to the question whether the development or absence of the microcline zone might be dependent upon the character of the central nucleus, I inspected the samples of the Kangasniemi rock in the collections of the University Museum, the Geological Commission, and the Technical University in Helsinki. Twenty-two polished slabs and two large specimens were inspected, containing in all thirty-four orbicules with visible central nuclei. Five of these show a massive igneous rock structure, being probably all quartz-dioritic, like the one described above, while seventeen were hornblende- or biotite-gneisses. The microcline zones were mostly broad, sometimes narrow, and rarely altogether absent, with no relation at all to the character of the central fragment. Frosterus[12] concluded from his observations that the development of the microcline zone depends upon the shape of the fragments, but even this is not the case. Apparently the material of the zones has been derived not from the nucleus but from the surrounding material.

The development of the microcline zone in the Kangasniemi orbicules belongs to those individual characters varying from orbicule to orbicule. Their development is generally variable, also, as regards the thickness of the zones. The Kangasniemi rock, as well as most other esboites with central fragments, also possesses orbicules which have remained at an embryonal stage, having only a thin shell enclosing the nucleus.

KORTFORS

Another classical orbicular rock is that from Kortfors, Sweden, well known from the excellent description by H. Bäckström.[13] From

[12] *Op. cit.*, p. 4.

[13] *Geol. Fören. i Stockholm Förh.*, Vol. XVI (1894); see also *ibid.*, Vol. XXVII (1905); *Jour. Geol.*, Vol. I (1893).

his observation that the most acid minerals form the kernel of the orbicules and more basic ones the mantle, Bäckström concluded that the orbicules had crystallized in the manner of secretions, or inward from outward, and that they had segregated as drops in a liquid state from the surrounding magma. Bäckström's hypothesis of liquation differentiation as a general explanation of rock differentiation was largely based upon this observation. As is well known, this hypothesis had very far-reaching consequences for petrogenetic ideas in general. It was therefore thought advisable in this connection to subject the different parts of the Kortfors esboite to a closer chemical investigation on the basis of material kept in our Museum.

The spheroidal orbicules possess a pegmatitic nucleus (Analysis 14, Table 2) composed of plagioclase, microcline, and quartz, with occasional big grains of dark-green hornblende and a little biotite. Graphic intergrowth of feldspar and quartz is common. The plagioclase shows $\alpha' = 1.540$, $\gamma' = 1.548$, pointing to the composition An_{22}. In the coarsely lamellar inner zone (Analysis 15) around the nucleus, the dominant plagioclase is a little more anorthitic (An_{24-26}), giving $\alpha' = 1.542$ and $\gamma' = 1.551$. Microcline and biotite are sparse, while hornblende and iron-ore grains are frequent. A radiating arrangement of the plagioclase parallel to the *a*-axis is an outstanding feature, while the hornblende is unoriented. In the mantles of the orbicules the plagioclase is the same throughout; while the quantity of hornblende and biotite at first increases toward the margin, and these minerals assume a tangential arrangement parallel to both the (100)-planes (hornblende) and the (001)-planes (biotite). The plagioclase is still radiating and so is a great part of the biotite and hornblende crystals, although the hornblende is prismatic at right angles to (100), and the biotite parallel to the *c*-axis (Fig. 9*e*). In the outer part of the mantle the hornblende and biotite decrease and the iron ores increase in quantity. The plagioclase assumes a tangential arrangement on its (010)-planes, as emphasized by Bäckström. The abundance of the iron ores and the more basic composition of the mantle appear from Analysis 16. All the zones of the orbicule show remarkably high [Fe]:[Mg] proportions, in accordance with the very dark colors of biotite and hornblende, both almost opaque for light vibrating parallel to their axes of greatest absorption.

The matrix is a typical hornblende-granite, granitoid in composition (Analysis 17) but largely pegmatitic. Its consanguinity with the orbicules appears only in the high [Fe]:[Mg] ratio, while its feldspar composition is very different, high in potash and very low in lime. The plagioclase shows $\alpha' = 1.537$ and $\gamma' = 1.545$ (An_{17}). The normative plagioclase is still more albitic, owing to the presence of much soda in the abundant microcline.

From a first summary, it may be said that the new investigation confirms Bäckström's conclusion that the sequence of the zones in the Kortfors orbicules is not that of normal crystallization differentiation. In the concluding section we shall see, however, that the crystallization cannot have proceeded inward from outward.

LINTUSAARI

In the autumn of 1936, Mr. Waller informed me that he had found, during a motorboat excursion on Lake Saimaa in southeast Finland, a boulder of orbicular granite on the western shore of the island Suuri Lintusaari, parish of Ruokolahti. I visited the island at the east side of the wide southern expansion of Lake Saimaa and found the boulder. From its position upon boulder-free esker sand it seemed to have been raised up on the strand from the lake bottom by the push of winter ice. The well-rounded boulder measured about 80 by 50 by 30 cm. It was made into polished slabs with the exception of a surface slab, which was left in its natural condition (Fig. 6*a*), and some fragments.

The Lintusaari rock shows many unique features and was the first to suggest, by the peculiar migmatitic character of its matrix, the new ideas about the esboitic crystallization presented in this paper. Fortunately, the contact of the orbicular rock against its wall rock, a monzonite, was preserved in the boulder. The transition takes place in such a way that at first some isolated orbicules appear in the monzonite (Fig. 6*b* and *c*) surrounded by narrow light-colored granitic border zones. These granitic zones grow broader, until the gray monzonite disappears as though assimilated altogether. Nebulitic remains of it, however, may be seen in most parts of the orbicular rock. This behavior necessarily suggests the thought that the orbicules had originated in the monzonite—or its magma—and that

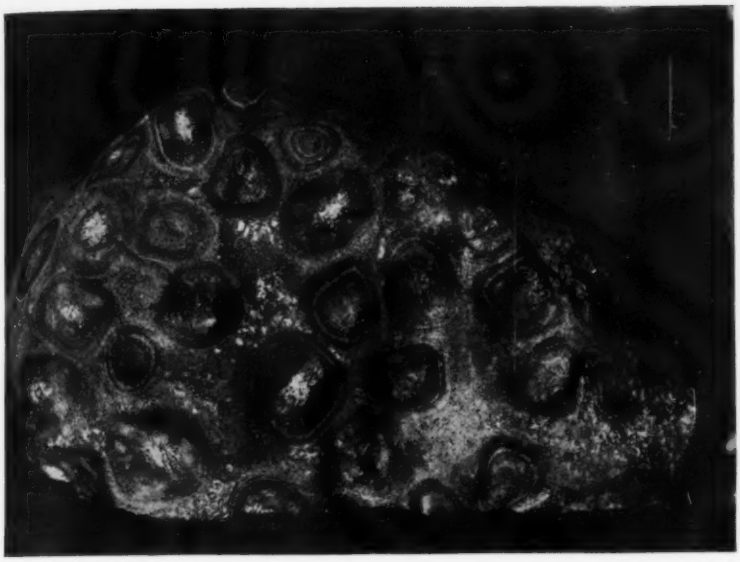


FIG. 6*a*.—Surface of the boulder from Lintusaari. Nuclei are plagioclase phenocrysts or crystal groups. Matrix migmatitic with remains of dark-gray monzonite. $\frac{1}{6}$ natural size.

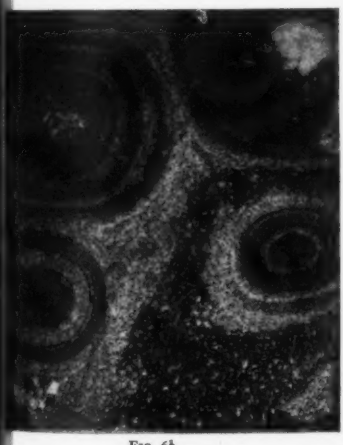


FIG. 6*b*

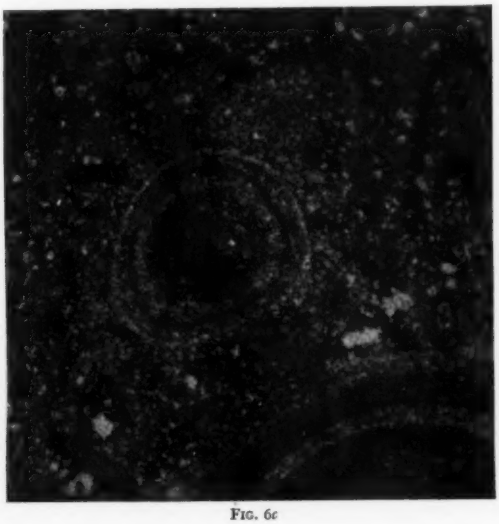


FIG. 6*c*

FIG. 6*b*.—Lintusaari. Contact against monzonite. $\frac{3}{4}$ natural size

FIG. 6*c*.—Lintusaari. Monzonitic country-rock with a single orbicule. $\frac{3}{4}$ natural size

the granitic matrix had later replaced the monzonite. This idea is strengthened by the fact that the outer zones of the orbicules have suffered strong corrosion, as may be seen in Figure 7*a*. In its upper left-hand quadrangle this figure shows an orbicule which has been neatly faulted about 1.2 cm., while no fault is visible in the granitic matrix near by. One-half of another orbicule is missing and the remaining half lies in the granitic matrix (Fig. 7*b*).

The central nuclei of the orbicules (Analysis 18, Table 3) are euhedral crystals of antiperthitic plagioclase, An_{20} ($\alpha' = 1.538$, $\gamma' = 1.547$), with some biotite (Fig. 7*a*). Many sections are quadratic, showing traces of (001), (201), and (010), while others show (110)-traces. The form is elongated along axis *c* or *a*, and thick tabular parallel to (010). Many of the polysynthetic phenocrysts are also Carlsbad contact twins with notched ends, as visible in Figure 7*a*. The nuclear phenocrysts frequently sent outside their euhedral boundaries irregularly bounded protuberances containing inclusions of quartz and biotite. These portions cannot be distinguished from the inner zone unless by means of reflections from the cleavage planes. The orbicules have assumed the shape of the nuclear phenocrysts, often showing conspicuously quadratic sections with rounded edges.

The surrounding zones mainly consist of granoblastic plagioclase of the same composition as the core; in the inner dark zone (Analysis 19) a partial radial arrangement is noticeable, while the plagioclase of the light shell (Analysis 20) is not at all oriented. The basal planes of biotite are arranged tangentially, but the crystals are thick and even prismatic along the *c*-axis (Fig. 9*f*). No microcline was observed in the shells of the Lintusaari orbicules, the potash content entering mainly into the biotite whose amount varies and causes the concentric banding seen in the photographs.

The monzonitic country rock (Analysis 21) which also occurs as the primary matrix between the orbicules (cf. above) is granitoid in structure. Myrmekite is common in the cross-hatched microcline. Numerous, rather big globules of yellowish zircon attract the attention. The chemical analysis shows a monzonitic composition, not common in the deep-seated intrusive rocks of Finland.

The granitic matrix (Analysis 22) belongs to that common kind of palingenetic granites which is nonhomogeneous and frequently

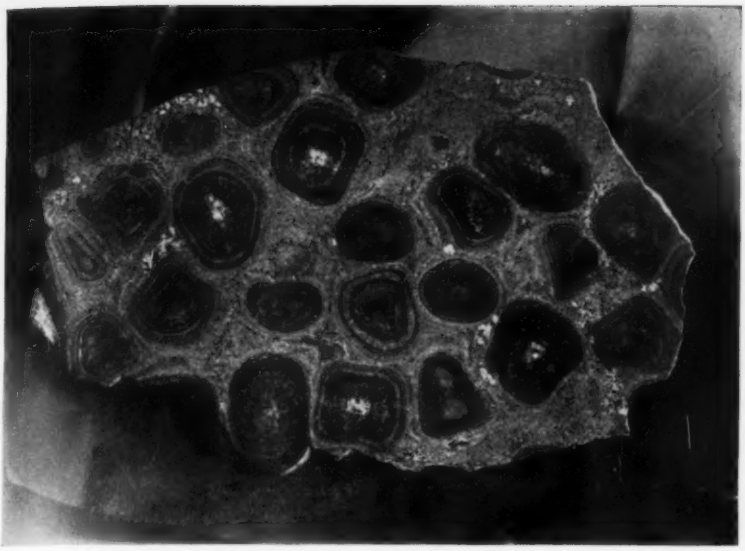


FIG. 7*a*.—Lintusaari. Orbicules with euhedral phenocrysts as nuclei, and migmatitic matrix with residual monzonite and plagioclase phenocrysts. Big orbicule in the left-hand side shows a fault. $\frac{1}{6}$ natural size.

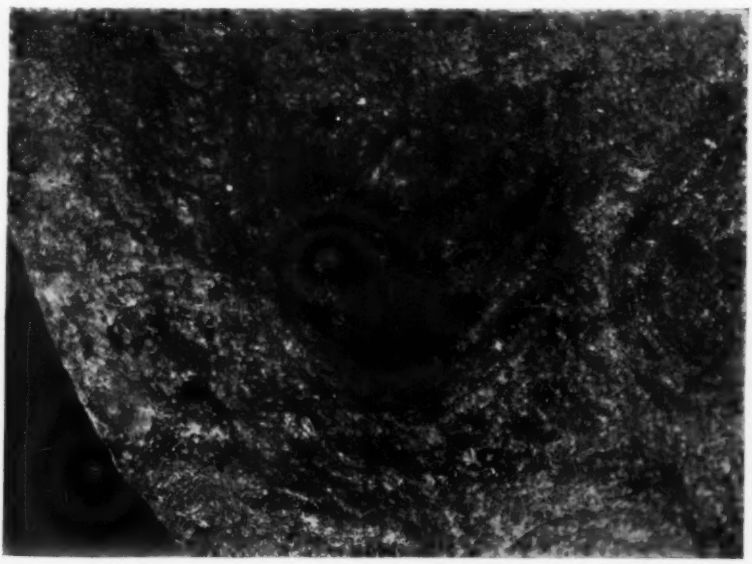


FIG. 7*b*.—Lintusaari. Rough surface. A broken orbicule, one half left, enclosed in granitic matrix. $\frac{3}{4}$ natural size.

pegmatitic in structure. Single big phenocrysts of plagioclase (An_{17-19}) occur in the light granitic matrix (Fig. 7*a*) just as in the monzonite (Fig. 6*c*).

TABLE 3

ANALYSES OF THE ORBICULAR ROCK FROM LINTUSAARI

	18	19	20	21	22
SiO_2	59.76	57.17	62.37	59.08	70.11
Al_2O_3	22.64	21.23	20.78	18.47	15.62
Fe_2O_3	0.48	1.45	1.05	1.25	0.59
FeO	2.16	4.79	1.95	5.83	1.29
MnO	0.02	0.01	0.02	0.03	0.02
MgO	0.54	1.39	0.47	1.55	0.36
CaO	4.36	3.86	4.16	2.44	1.07
Na_2O	6.72	5.95	7.08	4.39	3.07
K_2O	1.77	2.36	1.64	4.80	6.98
TiO_2	0.44	0.98	0.40	1.28	0.31
P_2O_5	0.01	.....	.....	0.02	0.01
H_2O+	0.83	0.84	0.41	0.87	0.43
H_2O-	0.01	0.04	0.03	0.13	0.03
Total	99.74	100.07	100.36	100.14	99.89
	NORMS				
q	2.38	0.57	4.30	3.97	21.96
or	10.49	14.47	9.81	28.47	41.36
ab	57.02	50.50	60.07	37.24	26.04
an	21.59	19.19	20.00	12.13	5.22
cor	2.23	1.83	.....	1.54	1.05
wo	.....	.....	0.29	.....	.....
fs	2.66	5.35	2.09	7.62	1.40
en	1.35	3.47	1.17	3.84	0.89
mt	1.11	2.11	1.53	1.81	0.86
il	0.84*	1.85	0.76	2.43	0.59

* Includes ap 0.03.

18. Feldspathic nucleus of orbicule. Lintusaari, Finland.
19. Dark-colored inner zone of orbicule. Lintusaari, Finland.
20. Light-colored outer zone of orbicule. Lintusaari, Finland.
21. Gray monzonitic matrix. Lintusaari, Finland.
22. Red granitic matrix. Lintusaari, Finland.

KEMIJÄRVI

In the summer of 1937, Mr. A. Simonen, during prospecting work in the parish of Kemijärvi in north Finland, discovered a new, most interesting occurrence of orbicular granite in place near Lake Kallio-

järvi in the western part of the parish and made a preliminary petrographic map of the locality. He intends to publish detailed results of his survey at a future date after revision in the field.

The orbicular rock underlies an elongated area of 23 by 2 meters surrounded partly by coarse-grained hornblende-rich granodiorite and partly by fine-grained light-red migmatitic granite, which is also intruded in the granodiorite. The map and field notes of Mr. Simonen give a picture of the relations of these rocks to the orbicular granite very similar to that of the Lintusaari rock: On the boundary the large orbicules appear as undisturbed regular spheroids in the mass of the country rock, either granodiorite or granite, and the matrix in the whole orbicular rock mass consists partly of the former, partly of the latter, and partly of a migmatite of both. The primary matrix is granodiorite.

In some of the orbicules there is a central nucleus containing hornblende and similar in structure to the granodioritic matrix. In others, coarse-grained plagioclase with some quartz, iron ore, chlorite, and epidote forms the center of the orbicule (Fig. 8*a*). As determined by the maximum extinction angle in the zone perpendicular to *M* (8°), and the values of α' (1.536) and γ' (1.545), the plagioclase is An_{15} or An_{16}. The core passes gradually into a more fine-grained granoblastic aggregate, mainly of plagioclase, whose composition is somewhat more anorthitic than that of the core, showing an extinction angle of 4° and $\alpha' = 1.539$, $\gamma' = 1.546$, corresponding to An_{19}. This zone, dark from iron-ore grains, is surrounded, with an absolutely sharp boundary, by a salmon-red shell mainly consisting of radiating microcline broadening outward and prismatic along the *a*-axis. The microcline contains abundant elongated inclusions of quartz with no apparent lattice orientation. No plagioclase in any form is visible in the microcline zone. The border of the orbicule against the matrix is again quite sharp.

The granodioritic matrix is coarse-grained and granitoid in structure. Plagioclase is the most plentiful and most idiomorphic constituent. Remarkably enough, it is considerably more anorthitic than the plagioclase of any part of the orbicules. Its maximum extinction angle in symmetrical sections was found to be 10°, and $\alpha' = 1.543$, $\gamma' = 1.550$, indicating a composition of An_{26} or An_{28}.

FIG. 8*a*.—Kemijärvi. Rough specimen. Part of an orbicule with a feldspathic nucleus, an inner coarse-grained and a second fine-grained plagioclase zone, and a radiating microclinic shell. A little of the granodioritic matrix is visible. $\frac{5}{6}$ natural size.

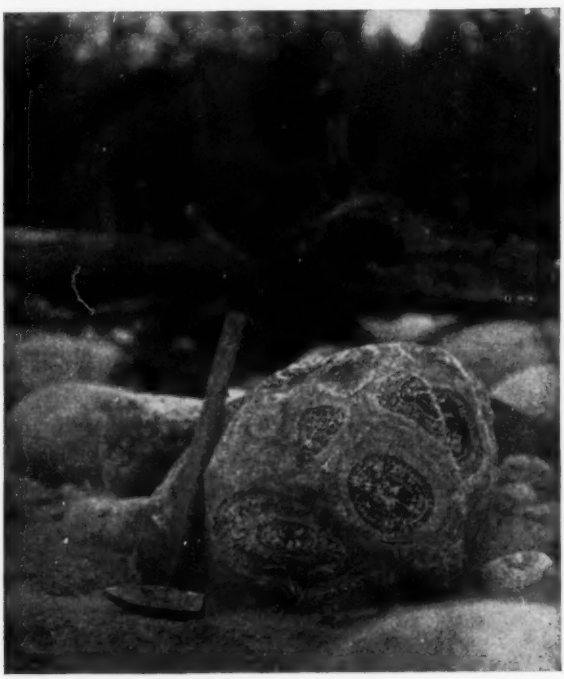


FIG. 8*b*.—Kurumkan, Transbaikalia. The orbicules in the boulder show a megascopic "warp and weft texture."

FIG. 9*a*

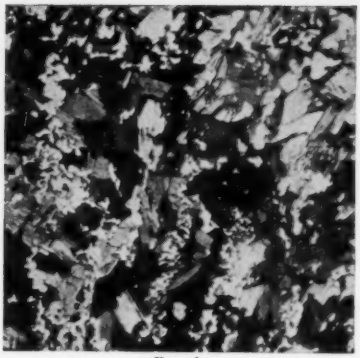


FIG. 9*b*

FIG. 9*a*.—Pöytyä. Outer zone of orbicule. Granoblastic plagioclase. ×18. Nicols crossed.

FIG. 9*b*.—Mäntyharju. Dark shell of orbicule. Mainly tangentially arranged biotite parallel to (001), and hornblende parallel to (100). Biotite thick tabular or prismatic parallel to *c*-axis, and hornblende elongated perpendicular to (100). ×18. One Nicol.

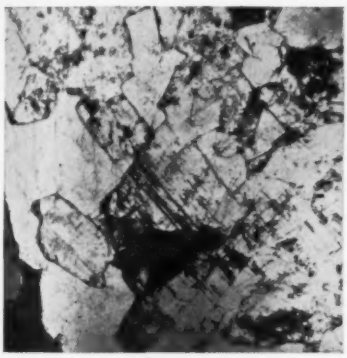


FIG. 9*c*

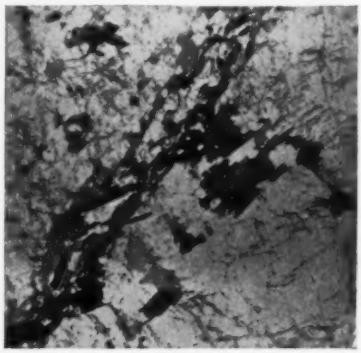


FIG. 9*d*

FIG. 9*c*.—Mäntyharju. Quartz-dioritic matrix. Idiomorphic plagioclase with quartz and biotite. ×18. One Nicol.

FIG. 9*d*.—Hankasalmi. Boundary between inner radiating plagioclase zone and shell with tangentially arranged biotite. The biotite scales are lying flat upon the tops of the plagioclase lamellae (lower right hand). ×18. One Nicol.

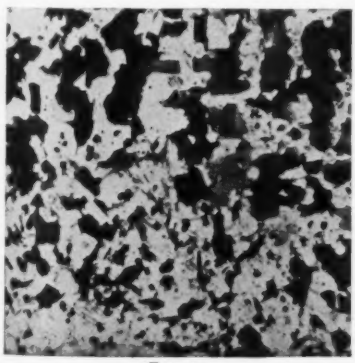


FIG. 9*e*

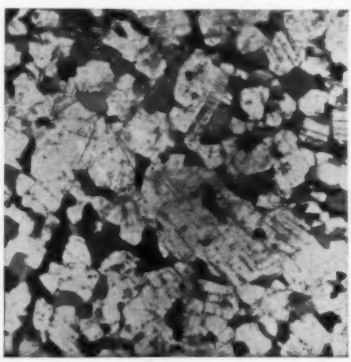


FIG. 9*f*

FIG. 9*e*.—Kortfors. Shell of orbicule. Hornblende elongated radially perpendicular to (100) in a granoblastic plagioclase mass, with iron ore grains. ×18. One Nicol.

FIG. 9*f*.—Lintusaari. Shell of orbicule. Biotite arranged tangentially parallel to (001) but elongated parallel to *c*-axis. ×18. One Nicol.

The light-red, fine-grained matrix is a potash-rich granite of a common type. Its plagioclase has approximately the same composition as that of the center of the orbicule, or An_{16}.

The orbicular granite of Kemijärvi is, in spite of many differences, an instructive counterpart to the Kangasniemi rock. Together, especially by their microcline zones, they throw much new light on the problem of the orbicular rocks, as will be discussed in the concluding section.

KURUMKAN

A photograph of the Kurumkan rock (Fig. 8*b*), whose discovery by Professor Viskont was mentioned in the introduction, shows well the typical "warp and weft texture" of the orbicules on a megascopic scale. The material at my disposal did not allow of any investigation of the different zones. The thin section of the orbicule shows much the same structure as the Pöytyä rock. Its plagioclase is oligoclase, showing in a section at right angles to *PM* an extinction angle of 22°. Brownish-green hornblende, colorless diopside, and brown biotite are present but no quartz nor potash feldspar. The matrix is biotite-hornblende-diorite.

DISCUSSION AND CONCLUSIONS

Nature of nuclei.—We may accept the proposal of F. Loewinson-Lessing and Olga Vorobjeva[14] to classify the orbicular rocks into allothrausmatic (with foreign nuclei), homeothrausmatic (with symmagmatic inclusions as nuclei), and isothrausmatic (the nuclei consist of the same rock as the matrix). One more type may be added: those in which early phenocrysts form the nuclei, as is so clearly the case in the Lintusaari rock. We can, temporarily, call it the "crystallothrausmatic type," noting at the same time that the nucleus is really no fragment (*θραῦσμα*) in this case. The Virvik, Fonni, and Balungstrand[15] rocks clearly belong to this type, and

[14] "Contribution to the Knowledge of Orbicular Structure in Igneous Rocks," *Compt. Rend. Acad. Sci. U.S.S.R.* (1929), pp. 351–56 (cited by Johannsen, *op. cit.*, p. 249).

[15] H. Bäckström, *Geol. Fören. i Stockholm Förh.*, Vol. XVI (1896), p. 121.

why not also the Hankasalmi and Kortfors rocks? It is true that the nuclei in the latter two rocks consist of graphic feldspar, but in pegmatitic rocks such segregations do occur, and the evidence of their occurrence as nuclei would only be that the orbicules have originated at a late stage in the crystallization, as is apparent from many other facts. If they are not authigenous crystallizations in the rock but instead allothogenous fragments of pegmatite, their role as nuclei would still be the same.

In the Laukaa and Mäntyharju rocks several kinds of nuclei occur, ranging from graphic feldspar to hornblendite. The Kangasniemi rock displays a similar diversity of nuclei. We may, to continue creating terms of Greek derivation in the manner of Loewinson-Lessing and Vorobjeva, speak of a" heterothrausmatic" type.

Now it is apparently most important to note, as we saw in the Kangasniemi, Laukaa, and Mäntyharju rocks, that the development of the orbicules is not dependent upon the composition of the nuclei, as similar zones have formed around basic and acidic nuclei, and apparently may form also around foreign and authigenous nuclei, and around feldspar phenocrysts. This means that the orbicules are not products of reactions between the nucleus and surrounding substance; and, consequently, they must have originated from the material of the matrix by diffusion and concretionary crystallization.

In the Kangasniemi, Kangasala, Esbo, and many other rocks a large part of the orbicules have no nuclei at all, and the growth of plagioclase zones, mostly radiating, has simply commenced from the central point. No doubt, small fragments may have disappeared by resorption, but there exists no necessity for such an assumption, as even spontaneously crystallized phenocrysts may start the concretionary formation of the orbicule.

Isothrausmatic orbicules possessing nuclei exactly similar to the matrix are fairly common. The Stockholm, Beverly Sound, Mullaghderg, Slättmossan, and Puutsaari rocks are well-known examples. Such orbicules in the Pöytyä and Mäntyharju rocks were described above. Their nuclei may be said to have formed by auto-

brecciation (Loewinson-Lessing and Vorobjeva), but it is rather difficult to form a clear idea about the mechanism of this process. Some help may be found in embryonal orbicules which, in many other respects, throw light upon the genesis of the orbicules.

It is now recommended that the reader look at Plate I, Figure 1, in Sederholm's memoir, showing the Puutsaari rock. An embryonal orbicule is visible between the three bigger ones, to the right in the figure. It consists of an ellipsoidal body of the matrix surrounded by an indistinct shell of plagioclase. (In reality it is more distinct in the polished slab, now kept in our museum.) We shall postpone for a while the question whether the surrounding material was liquid or crystalline at the time when the plagioclase shell originated and only note that the material of the core of the orbicule is identical with that of the surrounding matrix and proceed to consider the crystallization of the zones of the orbicules and of the matrix.

Composition of the feldspars.—Feldspars, and more especially plagioclases, are the active minerals determining the structure of the esboitic orbicules. Their compositions in different parts of the orbicules and matrix are shown in diagrams. Figure 10 shows the composition of the actual plagioclase as determined by optical methods. The matrix has sometimes the same plagioclase as the orbicules, but mostly a little more albitic, and often much more albitic (e.g., as in the Corsica, Kangasniemi, Hankasalmi, and Lintusaari rocks). The Corsica rock with its bytownitic plagioclase stands alone among all the orbicular rocks, and its orbicules possess the character of true crystallization differentiations. The remaining three have a migmatitic matrix, and a great hiatus occurs between the latest portion of matrix and the plagioclase-rich zones of the orbicules, whereas their primary matrix, when preserved, may contain nearly the same plagioclase as the orbicules. This is especially clear in the case of the Hankasalmi rock. It was this feature in the Lintusaari rock that first aroused my suspicion that its orbicules, apparently formed while surrounded by the monzonitic material and at the expense of substances derived from the latter by diffusion, might have formed in connection with the migmatitization. This suspicion was greatly strengthened by the interesting relations dis-

covered later in the Kemijärvi rock, which possesses a primary granodioritic matrix with much more anorthitic plagioclase and, in general, a more basic composition than the latest granitic matrix. In the diagram the point representing the plagioclase of the orbicule of this rock almost coincides with that of the latest migmatitic matrix, while the point representing the primary matrix lies far off to the left. The conclusion seems unavoidable that the formation

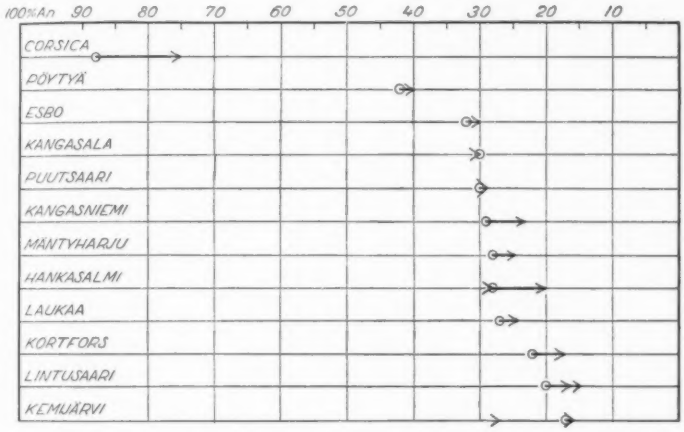


FIG. 10.—The composition of plagioclase according to optical determinations. Ring = orbicule; arrowhead = matrix. Double arrows mean that the rocks have two kinds of matrix; the later (migmatitic) matrix always contains more albitic plagioclase than the primary matrix.

of orbicules in this case has occurred during the migmatitization and from the substances added by this process.

In Figure 11 the compositions of the normative feldspars, or the [or]:[ab]:[an] proportions are shown for some orbicular rocks. By this method of projection the orbicular rocks with mainly feldspathic orbicules may be classified in five groups showing significant differences:

1. The Corsica rock, standing alone near the anorthite corner.

2. The true esboites in which the matrix as well as the orbicules are esboitic: Pöytyä, Esbo, Slättmossan, Kangasala. From the

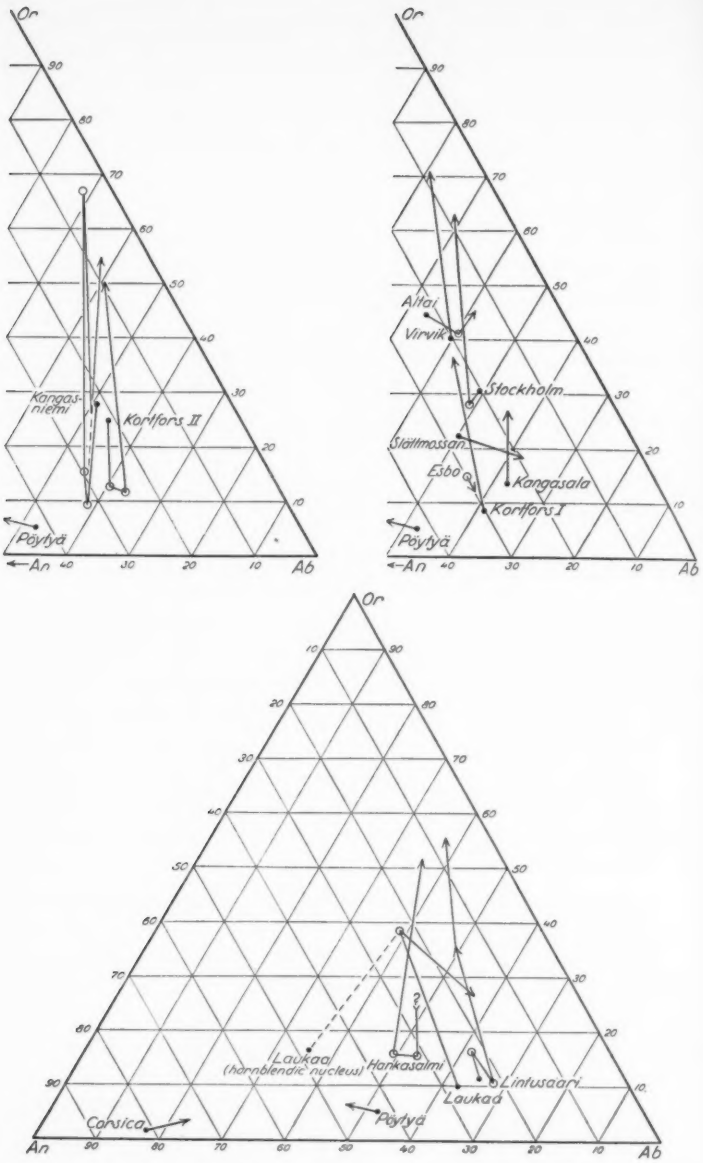


FIG. 11.—Normative feldspars of orbicular rocks according to analyses published in this paper (below and left hand side above) and in Sederholm's memoir (above to the right). The analyses of Hankasalmi rock are still unpublished. For the Kortfors II matrix, Analysis 17 gives (erroneously?) some femic lime although no mafic lime-bearing minerals occur; all the lime was in this case allotted to anorthite.

description, the Puutsaari rock is another typical representative; the Beverly Sound, Quonochontoque, Mullaghderg, and Kurumkan rocks also belong to this group. In the Pöytyä rock the normative plagioclase is more anorthitic in the matrix, the excessive anorthite being actually contained in the hornblende. In the Kangasala rock the matrix is richer in potash, this rock being transitional to Group 4.

3. In the type of Laukaa (and Mäntyharju) various nuclei, some esboitic, others hornblendic, are surrounded by thin esboitic inner zones (not analyzed), and these by a dark shell rich in biotite and hornblende and high in potash. The matrix is more esboitic in the Laukaa rock and apparently still more so in the Mäntyharju rock. These features indicate a profuse diffusion of Fe and Mg toward the orbicules, but otherwise no great divergencies from the normal esboitic crystallization, and the structure of the shells is typical of the esboitic orbicules (cf. below).

4. Esboitic orbicules in a granitic matrix: Hankasalmi, Kortfors, Lintusaari. In the first two mentioned the zones of the orbicules only are esboitic, whereas their nuclei (in the Hankasalmi rock not analyzed) are of various kinds, often very potash-rich, the composition of the nucleus being a matter of no importance for that of the orbicule.

The Hankasalmi rock possesses a migmatitic matrix, and the best-preserved portions of its older component are still esboitic, containing a plagioclase identical with that of the orbicules (Fig. 10). Some orbicules are now surrounded by big lumps of quartz. Many orbicules have been greatly resorbed (Fig. 5*a*). These and other features are good arguments for the opinion that the orbicules of the Hankasalmi rock were originally surrounded not by the present matrix but rather by the primary matrix, which was later replaced by pegmatitic material. Similar evidences of later replacement of the primary matrix in the Lintusaari rock were given in the description of it above.

The specimens of the Kortfors rock at my disposal show no evidence of migmatitization. The matrix is pegmatitic but fairly homogeneous. In this case esboitic orbicules seem to have separated out from a granitic material. The same is well illustrated in many

rocks of the next group. The Balungstrand rock may also belong to Group 4.

5. Orbicules and matrix are mainly granitic in bulk composition but the former often possess recurrent zones of esboitic and "microclinic" composition: Kangasniemi, Stockholm, Virvik, Altai, Kemijärvi. In the Kangasniemi rock the two kinds of zones are mostly well differentiated. An analogous recurrence exists in the Virvik rock, with a less sharp contrast of the zones but with a far greater number of recurrent zones. The Stockholm orbicules are mostly poorly differentiated, but even in them microclinic zones appear, as described by Brögger.[16] The Kemijärvi rock is a most interesting representative of this group. In it the migmatitic but not the primary matrix is granitic, and the orbicules, similar to the later matrix in bulk composition, are extremely sharply differentiated into esboitic inner zones and a microclinic shell, the latter showing no trace of corrosion.

Structure of orbicules.—Lamellar shape and radiating arrangement of plagioclase, and still more of microcline, is a conspicuous feature. The lamellae, as a rule, are elongated parallel to the *a*-axis, which is the pseudotetragonal axis of feldspar. This arrangement was already noticed by Brögger[17] and Frosterus.[18] It is, however, no inherent character of esboitic crystallization. Instead of it the plagioclase mass frequently shows a typical granoblastic structure. As a rule, the inner plagioclase zone is more coarse-grained and radiating, while the outer zones are granoblastic.

Both structures of plagioclase in the orbicules are combined with a concentric schistose arrangement of biotite and hornblende in the outer zones. Radiating plagioclase and tangential biotite often show the "warp and weft texture,"[19] layers richer and poorer in biotite alternating, and plagioclase playing the role of warp and biotite that of the weft (see microphotos in Sederholm's memoir). It is fairly clear from microscopic observation that the schistosity of the biotite-rich zones is due to the crystallization pressure of the plagioclase (Fig. 9*d*). The radiating lamellae have mechanically com-

[16] W. C. Brögger och Helge Bäckström, *Geol. Fören. i Stockholm Förh.*, Vol. IX (1887).
[17] *Ibid.*, p. 336. [18] *Op. cit.*, p. 16. [19] Sederholm, *op. cit.*, p. 32.

pressed the mafic crystals, part of which probably existed before the crystallization of the orbicules. Frosterus[20] already assumed a mechanical concentration of biotite, although his idea of this process was somewhat different from the present interpretation. During the growth of the orbicule the crystals of biotite and hornblende in tangential arrangement may have grown more and attained the uncommon prismatic habit of hornblende perpendicular to (100), as described from the Mäntyharju and Kortfors rocks, and of biotite parallel to the *c*-axis, e.g., in the Lintusaari rock. At the margin, even the plagioclase has sometimes assumed a tangential orientation parallel to (010), e.g., in the Kortfors and Lintusaari orbicules.

All these structural features clearly prove that the crystallization of the orbicules has proceeded outward from the nucleus. In the Kangasniemi and Pöytyä rocks, among others, we have also secretionary crystallizations in original drusy cavities, and these show quite different structures.

Genesis.—As we approach the most remarkable result of this study, we must recapitulate some important facts. The Corsica rock is the only orbicular rock showing a relation of orbicules to matrix consistent with the current idea of crystallization of orbicules from a liquid magma. For the "true esboites" application of this idea meets with difficulties: (1) the amount of albite does not increase from orbicule to matrix or does so less than should be expected; (2) the sequence of the zones of orbicules and the occurrence of pegmatitic nuclei is often contradictory to the laws of magmatic crystallization; and (3) many examples of this group are isothrausmatic, having portions of the matrix as nuclei. The power of evidence, though perhaps not quite decisive, is decidedly in favor of the idea that the matrix was solid, or at least contained a solid sponge of early formed crystals, at the time of the crystallization of the orbicule.

Especially for the Pöytyä rock, which I have been able to study most closely, it long seemed plausible to me that the formation of

[20] *Op. cit.*, p. 29.

orbicules had occurred at a late stage of magmatic consolidation, when the diorite was a mush of crystals and magma. Even in this rock, however, the possibility is not excluded that the orbicular structure originated during an epoch of granitization, when the rock had long been solid. In the Esbo, Kangasala, and Kortfors rocks this seems decidedly the more probable explanation. In any case, the concretionary crystallization was due to a metasomatic replacement of pre-existing minerals.

The features observed in the Lintusaari and Hankasalmi rocks may make the foregoing reasoning intelligible. Their matrix is migmatitic, and its older portion, already called the primary matrix, is in substance similar to that of the Esbo rock, the prototype of orbicular esboites. Consequently, they once were true esboites. They may have been formed during the primary crystallization as was thought possible for the Pöytyä rock. But the orbicular rocks, in Esbo and elsewhere, show such a close connection with migmatites that a genetic connection between them must be suspected. When the approaching migmatite front had opened the doors for free diffusion, one of the early effects of this may have been to start esboitic crystallization wherever favorable materials and structures existed.

For some reason not yet understood the esboitic material is most adapted for diffusion and concretionary crystallization. Orbicular granites are much rarer than orbicular esboites. The former also occur in migmatitic surroundings, as in Stockholm and Virvik. The materials of their orbicules have been derived from the granitizing ichors. As a rule, they differentiated into the esboitic and microclinic zones of the orbicules.

The Kemijärvi rock is the most illuminating example so far known of this process. The orbicules are embedded in a granodiorite. Their material has not, however, been derived from this rock but instead from the injected granitizing ichors. This orbicular granite may positively be said to have originated through a process of metamorphic differentiation by the concretion principle. Perhaps this is the true explanation of many if not all orbicular esboites and granites. This explanation helps us out of the difficulties just mentioned, but it also arouses a long series of new questions. Or, rather, it is the

possibility of the genesis of orbicular rocks by metamorphic differentiation, now positively established, that arouses new problems for petrologic science.

ACKNOWLEDGMENTS.—The chemical work was executed by Miss Elsa Ståhlberg. In the optical determinations and in calculating the analyses I was assisted by Miss Anna Hietanen and Mr. A. Simonen. For their valuable help I thank them very much. Further, I wish to thank Dr. H. Väyrynen, geologist of the Geological Commission of Finland, who gave me for investigation the boulder of orbicular granite, found in Mäntyharju and presented by him to the University Museum; Mr. E. Vaheri, A.M., student of geography, who brought me specimens of orbicular rock found by him in Laukaa; Mr. K. R. Waller, student of chemistry, who informed me about the boulder of orbicular granite that he had found on the island Lintusaari; and Mr. A. Simonen, student of geology, who put the whole material of his new discovery of orbicular rock in Kemijärvi at my disposal.

PETROGRAPHIC AND CHEMICAL DATA ON THE CANADIAN SHIELD

FRANK F. GROUT
University of Minnesota

ABSTRACT

This paper presents thirty-nine new analyses and petrographic notes on igneous rocks of the Canadian Shield. Attention is called to some peculiar rocks and to the probable bearing of the results on calculations of the composition of the Shield.

Clarke and Washington in 1924 called attention to the fact that their average of analyses of rocks from Canada is not representative of the northern half of North America because of our ignorance of the vast expanse of country north of the areas whose rocks are known.[1] Since the Canadian Shield is an area of two million square miles (Fig. 1), it will, of course, be many years before the rocks are well known, but this paper makes a start on some little-known portions of it by offering a number of new analyses and some discussions.

These analyses have been made largely in the University of Minnesota Laboratory for Rock Analysis, generously assisted by the Geological Society of America. The assistance from funds of the Graduate School of the university is also gratefully acknowledged. Several graduate students and others who assisted by collecting samples on their summer expeditions are mentioned in connection with the descriptions of samples.

The tables of analyses and brief petrographic notes are here presented in very condensed form. Each available rock has been studied in thin section, and notes are given as to the actual minerals, so that it can be classified by the mode as well as by the norm. Some of the rocks are coarse and streaked, however, so that a thin section gives a much less accurate sample than that crushed for analysis.[2] The

[1] F. W. Clarke and H. S. Washington, "The Composition of the Earth's Crust," *U.S. Geol. Surv. Prof. Paper 127* (1924), p. 44.

[2] E. S. Larsen and F. S. Miller, "The Rosiwal Method and the Modal Determination of Rocks," *Amer. Mineral.*, Vol. XX (1935), pp. 260–72.

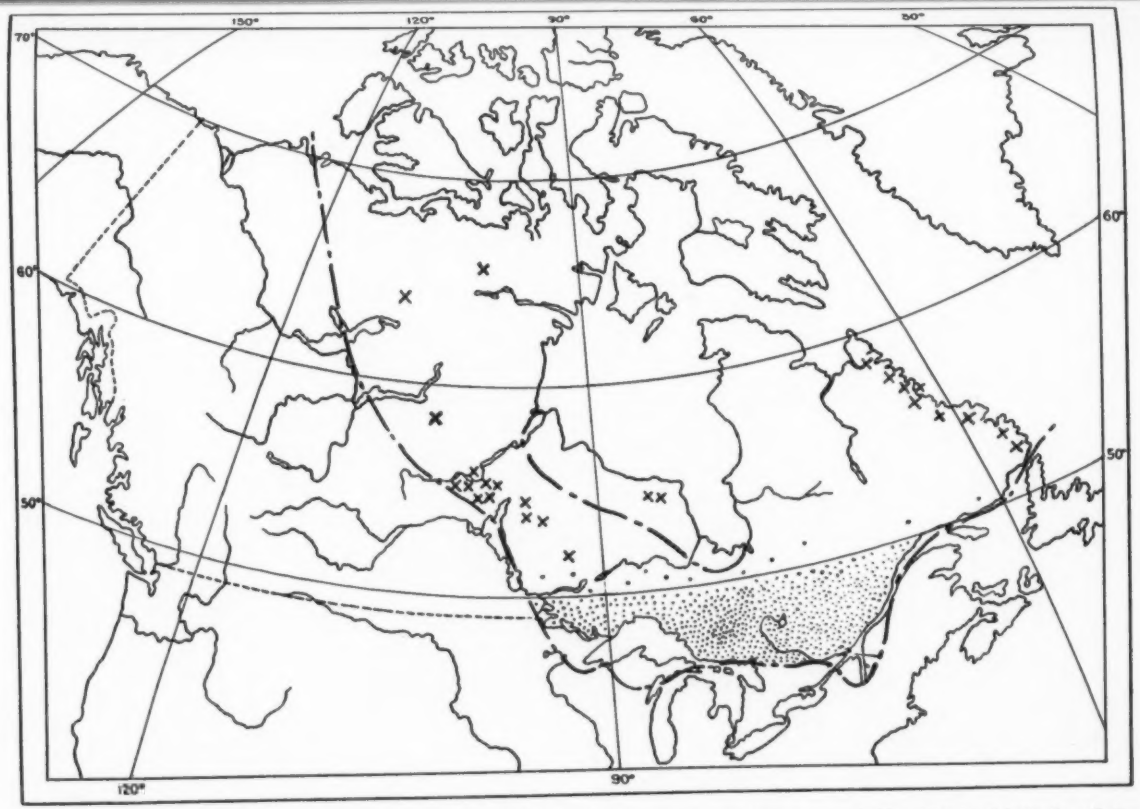


FIG. 1.—Sketch of the Canadian Shield. Stippled area shows where many rock analyses are available. North of latitude 51° the approximate locations of rocks analyzed are shown by crosses.

Rosiwal measurements have therefore been reported in rough figures only. Several rocks which are near division lines in some system of classification may fall into different groups according to whether the chemical work or microscopic study is believed most dependable. As examples: Specimen 8 is near the line of Orders 1 and 2, and Families 6 and 7 of Johannsen's classification; Specimen 10 is near the line of Classes 1 and 2, Orders 1 and 2, and Families 6 and 7 of the same system; Specimen 32 is near the line between Orders 3 and 4, Rangs 2 and 3 of the C.I.P.W. system.

FIG. 2.—Granite from the Creighton Mine; the large piece (brecciated) gave Analysis 14.

PETROGRAPHIC COMMENTS

In summary of the norm classification of the thirty-nine new analyses: thirty-one fall in Class I, thirty-one fall in Order 4, twenty fall in Rang 2, and twenty-six fall in Subrang 3. Clearly the commonest rock is I.4.2.3 which is toscanose, and ten actual samples fall in this subrang.

The only rock in Rang 4, docalcic, is from Kississing Lake. The only rock in Subrang 2, dopotassic, is from Winnipeg River. The two rocks in Subrang 5, persodic, are a Laurentian gneiss from Rice Bay of Rainy Lake and a Killarney (?) granite from Birch Lake.

Specimen 11.—Dr. Collins had the Birch Lake granite collected by Dr. Ellsworth as "typical Killarney" but later gave evidence for an age between the nickel eruptive and the Huronian sediments.[3] In view of the high soda content, and Dr. Collins' expressed opinion that Killarney granites have higher potash than soda, the Killarney age is questioned, but the granite does look somewhat like other Killarney specimens. It certainly *has high soda*, illustrating a group in Johannsen's classification for which he has but four measured examples and three analyses, Group 217P.

Specimen 17.—This is another persodic rock, but the concentration is less extreme.

The rock recently described by Lindner as persodic is also a Canadian specimen,[4] and a Canadian rock from Island Lake[5] approaches the persodic group—in Johannsen's table it is 217P.

Specimen 16.—This rock appears to be a large, rather irregular lamprophyre dike (malchite to vogesite) in the Saganaga granite. The granite near it, however, is much darker than average and shows gradations as if by contamination or differentiation in a different way from that commonly assumed for lamprophyres. The minerals have been separated in heavy liquids and stained and counted by Dr. S. W. Sundeen[6] to determine their proportions more accurately than by Rosiwal measurement. Even with very careful work the dustiness of the feldspar makes the determination difficult. Over three-fourths of the grains that show multiple twinning have indices of refraction less than 1.535, and the rest are near that. They are listed as albite. The data show that the rock is a mela-sodaclase-granodiorite in Johannsen's classification and fills a space in the scheme for which he had no example analyzed, 317D. It may be added that a similar rock occurs as a facies of the Giants Range batholith in Minnesota, so that there are probably examples of 317P.

[3] W. H. Collins, "The Life History of the Sudbury Nickel Eruptive," *Trans. Roy. Soc. Can.*, Vol. IV (1936), pp. 29–53.

[4] J. L. Lindner, "The Dynamic Metamorphism of a Pegmatite," *Jour. Geol.*, Vol. XLV (1937), pp. 558–63.

[5] F. F. Grout, "Ages and Differentiation Series of the Batholiths Near the Minnesota-Ontario Boundary," *Bull. Geol. Soc. Amer.*, Vol. XL (1929), p. 807.

[6] Thesis, University of Minnesota, 1936.

TABLE 1

ANALYSES OF LYNDHURST, ONTARIO, BATHOLITH AND RELATED ROCKS*

	1	2	3	4	5	6
SiO_2	71.02	60.81	68.85	60.40	68.78	71.35
Al_2O_3	13.39	15.34	14.26	16.12	16.72	13.40
Fe_2O_3	1.66	3.47	1.57	2.09	0.08	1.20
FeO	1.33	2.87	1.62	4.71	2.22	1.59
MgO	0.68	1.99	0.99	2.87	3.00	0.79
CaO	1.19	3.10	1.48	4.54	3.60	1.00
Na_2O	3.04	3.64	3.17	2.96	2.58	2.98
K_2O	6.14	5.30	5.92	2.40	2.29	5.96
H_2O+	0.27	0.68	0.40	1.76	0.80	0.38
H_2O-	0.04	0.07	0.04	0.38	0.04	0.03
CO_2	0.24	0.22	0.16	.....	.....	0.18
TiO_2	0.62	1.37	0.80	1.25	0.27	0.62
P_2O_5	0.34	0.67	0.34	.....	.....	0.27
S	.....	0.07	.....	.....	.....	.....
MnO	0.05	0.09	0.05	.....	.....	0.05
BaO	.....	0.13	.....	.....	.....	.....
Total	100.01	99.82	99.65	99.48	100.38	99.80
C.I.P.W.	I.4.1.3 Liparose	II.4.2.3 Adamellose	I.4.2.3 Toscanose	II.4.3.4 Tonalose	I.4.3.4 Yellowstonose	I.4.1.3 Liparose
Johannsen	215 Kaligranite	227 Granodiorite	226 Granite	.....	.....	226 Granite

* Collected by George Brownell; about latitude 45° N., longitude 78° W.

1. Lyndhurst pink granite, paving stone quarry. Percentages: microcline-perthite 65, quartz 25, biotite 4, and titanite 2; traces of other feldspars, magnetite, zircon, apatite, tourmaline, rutile, secondary kaolinite, chlorite, leucoxene, hematite, and added carbonate. T. Kameda, analyst.

2. Middle of Lyndhurst granite, pinkish gray, near quartzite inclusion. Percentages: oligoclase 30, quartz 20, microcline 20, orthoclase-perthite 10, hornblende 10, magnetite 5, and biotite 3; accessory zircon, apatite, titanite, rutile, and traces of alteration products. R. B. Ellestad, analyst.

3. Along edge of Lyndhurst pink granite for 1,500 feet. Percentages: microcline 30, perthite 30, oligoclase 15, quartz 15, biotite 3, and magnetite 3; accessory zircon, apatite, and a trace of hematite. T. Kameda, analyst.

4. Red granite, south of road, Sweet Corners, Lyndhurst. More biotite and titanite than No. 5, but no section now available. Reported in thesis by Brownell, University of Minnesota, 1928. George Ward, analyst.

5. White granite, ¼ mile north of Morton, Lyndhurst. No section available. Reported in thesis by Brownell, University of Minnesota, 1928. G. Ward, analyst.

6. Isolated stock of pink granite related to Lyndhurst granite. Percentages: microcline 35, quartz 25, oligoclase 15, orthoclase 5, biotite 10, magnetite 3, and titanite 2; accessory zircon, apatite, tourmaline, and traces of alteration products. T. Kameda, analyst.

TABLE 2

ANALYSES OF KILLARNEY GRANITES AND RELATED ROCKS*

	7	8	9	10	11	12	13	14
SiO_2	69.20	73.66	72.46	72.35	75.64	72.81	66.67	66.77
Al_2O_3	14.95	13.92	14.45	14.96	13.92	13.85	16.22	13.89
Fe_2O_3	1.09	0.33	0.08	0.09	0.11	0.92	1.53	1.52
FeO	1.71	1.03	1.74	1.82	1.21	1.04	1.67	4.15
MgO	1.13	0.48	0.55	0.64	0.65	0.62	0.91	1.66
CaO	1.14	1.30	1.50	2.14	0.29	0.63	1.49	2.94
Na_2O	4.14	3.61	3.08	3.56	6.69	3.04	4.58	3.17
K_2O	4.85	4.21	4.98	3.46	0.64	5.96	5.25	3.90
H_2O+	0.67	0.44	0.42	0.44	0.58	0.53	0.60	0.60
H_2O-	0.05	0.05	0.02	0.01	0.02	0.05	0.10	0.06
CO_2	0.26	.....	0.11	.....	.....	.....	.....	.....
TiO_2	0.44	0.19	0.28	0.29	0.15	0.32	0.58	0.69
ZrO_2	.....	tr.	.....	.....	.....	.....	.....	.....
P_2O_5	.....	0.30	.....	.....	.....	.....	.....	0.20
S	.....	tr.	.....	.....	.....	.....	.....	.....
Cr_2O_3	.....	none	.....	.....	.....	.....	.....	.....
MnO	.....	.....	.....	.....	.....	.....	.....	0.08
BaO	.....	0.02	.....	.....	.....	.....	.....	.....
Total	99.63	99.54	99.67	99.76	99.90	99.77	99.60	99.63
C.I.P.W.	I.4.2.3 Toscanose	I.4.2.3 Toscanose	I.4.2.3 Toscanose	I.4.2.3 Toscanose	I.4.1.5 Noyangose	I.4.1.3 Liparose	I.4.2.3 Toscanose	II.4.2.3 Adamellose
Johannsen	227 Rhyodacite	126 Leucogranite	226 Granite	226 Granite	217 Sodaclase-granodiorite	226 Granite	226 Granite	.....

* Collected by H. V. Ellsworth, north of Lake Huron.

7. Red felsite porphyry, tip of Phillips Edward Island, Killarney. Percentages: oligoclase 40, orthoclase 15, microcline 10, quartz 25, and biotite 5; accessory magnetite, apatite, titanite, zircon (?), and traces of alteration products. R. B. Ellestad, analyst.

8. Pinkish-gray granite of large area, Cutler and west. Percentages: oligoclase 30, microcline 25, orthoclase 10, quartz 30, biotite 3, and muscovite 2; accessory zircon, apatite, and traces of secondary minerals. R. B. Ellestad, analyst.

9. Gray granite, slightly gneissic, Serpent River. Percentages: microcline and orthoclase 38, oligoclase 25, quartz 30, and biotite 6; accessory muscovite, apatite, zircon, and secondary sericite, carbonate, and epidote. R. B. Ellestad, analyst.

10. Gray granite, C.P.R. railway cut about ½ mile west of Milepost 32. Spragge-Cutler, Ontario. Percentages: quartz 30, microcline 35, oligoclase 28, and biotite 5; small amounts of epidote, apatite, zircon, and muscovite. T. Kameda, analyst.

11. Typical pink Killarney (?) granite, Birch Lake, Webbwood, Ontario. Percentages: albite 45, perthite 10, quartz 35, and chlorite 6; accessory zircon and secondary quartz, sericite, hematite, and leucoxene. T. Kameda, analyst.

12. Pink granite gneiss, shore of Collins Inlet. Percentages: quartz 30, perthite 40, microcline 10, oligoclase 10, and biotite 8; accessory apatite, zircon, magnetite, ilmenite, allanite (?), and traces of secondary minerals. R. B. Ellestad, analyst.

13. Coarse pink porphyritic granite gneiss, north side of Collins Inlet. Percentages: microcline 25, oligoclase 25, orthoclase 20, quartz 20, and biotite 7; accessory hornblende, magnetite, zircon, titanite, apatite, allanite, and traces of secondary minerals. R. B. Ellestad, analyst.

14. Gray brecciated granite, Creighton Mine, Sudbury. A crushed epidotic matrix has quartz, feldspars, and biotite in remnants of granitoid grains. To compare with an analysis of pink granite of the Creighton Mine, published by Dr. W. H. Collins in *Trans. Roy. Soc. Canada*, Sec. IV (1936), p. 48. Lee Armstrong, analyst. (See Fig. 2.)

TABLE 3

ANALYSES OF ROCKS BETWEEN LAKE SUPERIOR AND WINNIPEG

	15	16	17	18	19	20	21	22
SiO_2	57.85	49.26	71.64	71.54	61.57	65.46	73.99	77.54
Al_2O_3	14.19	11.99	16.69	15.92	20.02	16.01	11.93	11.42
Fe_2O_3	2.65	3.78	0.39	0.07	0.61	1.50	2.11	0.63
FeO	3.36	6.87	0.70	0.74	2.28	2.72	0.77	0.96
MgO	4.62	8.23	0.67	0.43	1.89	1.95	0.41	0.26
CaO	9.01	9.88	2.61	1.95	6.45	4.20	0.94	0.76
Na_2O	5.03	2.82	5.26	5.41	3.84	4.74	2.15	2.92
K_2O	1.35	1.36	1.10	2.65	1.49	1.58	6.03	4.53
H_2O+	0.80	1.60	0.49	0.29	0.66	0.51	1.12	0.16
H_2O-	0.12	0.04	0.06	0.02	0.09	0.05	0.16	0.02
CO_2	.....	2.01	0.02	0.03	.....	.....	none	0.08
TiO_2	0.89	1.18	0.21	0.15	0.43	0.53	0.89	0.25
ZrO_2	.....	.....	none	0.03	.....	.....	0.06	0.05
P_2O_5	0.80	0.88	0.17	0.49	0.29	0.60	0.04	0.14
S	.....	.....	0.01	tr.	0.09	tr.	0.06	tr.
MnO	.....	0.14	0.02	0.02	0.04	0.09	0.02	0.03
BaO	.....	.....	0.07	0.08	.....	.....	tr.	0.07
Total	100.67	100.04	100.11	99.82	99.75	99.94	100.68	99.82
C.I.P.W.	II.5.2.4 Akerose	III.5.3.4 Camptonose	I.4.2.5 Mariposose	I.4.2.4 Lassenose	I.4.3.4 Yellowston-ose	I.4.3.4 Yellowston-ose	I.3.2.2 Mihalose	I.3.1.3 Alaskose
Johannsen	227 Granodiorite	317 Melasodaclase-granodiorite	127 Leucograno-diorite	127 Leucograno-diorite	227 Granodiorite	227 Granodiorite	126 Leucogranite	227 Granodiorite

15. Pink granite, Crow Rock Lake, north of Atikokan, Ontario, collected and analyzed by W. S. Yarwood. Percentages: oligoclase 55, hornblende 20, orthoclase 10, and quartz 10; accessory biotite, apatite, titanite, magnetite, and some hydrothermal attack.

16. Lamprophyre (or segregation). Saganaga Lake, Ontario. Percentages: hornblende 50, chlorite 5, epidote 2, carbonate 5, albite 15, orthoclase 12, and quartz 9; accessory apatite, magnetite, titanite, and pyrite. V. B. Meen, analyst.

17. Gray gneiss, probably Laurentian, Upper Rice Bay of Rainy Lake. Percentages: oligoclase 40, orthoclase 20, quartz 30, biotite 3, and muscovite 3; accessory titanite, apatite, and secondary epidote and sericite. T. Kameda, analyst.

18. Gray granite. Rice Bay of Rainy Lake. Percentages: oligoclase 43, microcline and orthoclase 20, quartz 30, biotite 3, and muscovite 2; accessory apatite, titanite, and secondary chlorite, epidote, and rutile. R. B. Ellestad, analyst.

19. Gray granite (quartz diorite) south of Goose Island, Lac Seul. Collected by F. J. Pettijohn. Percentages: basic andesine 55, orthoclase 10, quartz 20, and biotite 12; accessory apatite, zircon, magnetite, pyrite, and secondary chlorite, epidote, hematite, and kaolinite. R. B. Ellestad, analyst.

20. Gray gneiss, between Lac Seul and Grassy Lake. Collected by F. J. Pettijohn. Percentages: andesine 50, orthoclase 10, quartz 20, hornblende 10, and biotite 10; accessory apatite, magnetite, zircon, and slight weathering. R. B. Ellestad, analyst.

21. Pink, slightly gneissic granite, batholith, south of Winnipeg River near Minnesota. Collected by C. H. Stockwell. Percentages: oligoclase 30, microcline 20, orthoclase 20, quartz 25, biotite 2, and epidote 2; accessory apatite, titanite, magnetite, and traces of alteration. F. Grout and G. Ward, analysts.

22. Pink granite drill core from oil well, Stony Mountain, northwest of Winnipeg. A more gneissic piece of core than the one, analysis of which is given in *Bull Geol. Soc. Amer.*, Vol. XL (1929), p. 807. Percentages: oligoclase 40, microcline 20, quartz 25, and biotite 10; accessory epidote, magnetite, apatite, titanite, zircon, and slight weathering. R. B. Ellestad, analyst.

TABLE 4

ANALYSES OF GRANITES OF THE LABRADOR COAST*

	23	24	25	26	27	28	29
SiO_2	65.48	60.57	70.60	64.22	58.40	69.69	75.58
Al_2O_3	16.00	16.70	14.00	12.35	18.84	15.96	12.14
Fe_2O_3	1.53	4.63	1.54	6.17	1.61	0.58	1.21
FeO	2.06	2.13	1.62	2.94	3.84	1.60	1.03
MgO	1.40	1.05	0.71	1.14	1.71	0.85	0.16
CaO	1.43	1.43	1.62	2.30	3.74	2.29	0.62
Na_2O	3.78	4.47	3.74	3.88	4.45	3.73	3.52
K_2O	5.98	6.31	4.55	3.87	5.07	4.65	4.43
H_2O+	0.74	0.75	0.43	0.57	0.73	0.28	0.38
H_2O-	0.04	0.06	0.02	0.31	0.05	0.01	0.14
CO_2	0.08	.....	.....	.....	.....	.....	tr.
TiO_2	0.72	1.21	0.54	1.39	0.87	0.42	0.22
ZrO_2	0.06	.....	.....	.....	0.03	0.02	0.04
P_2O_5	0.25	0.28	0.20	0.39	0.33	0.17	0.09
S	0.06	.....	0.07	tr.	0.06	0.05	tr.
MnO	0.09	0.10	0.07	0.12	0.08	0.04	0.02
BaO	0.11	.....	0.12	0.15	0.03	0.03	none
Total	99.81	99.69	99.83	99.80	99.84	100.37	99.74†
C.I.P.W.	I.4.2.3 Toscanose	I.5.1.3 Phlegrose	I.4.2.3 Toscanose	II.4.2.3 Adamellose	II.5.2.3 Monzonose	I.4.2.3 Toscanose	I.3.1.3 Alaskose
Johannsen	226 Granite	226 Granite	227 Granodiorite	216 Sodaclase-granite	226 Granite	226 Granite	116 Alaskite

* Collected in 1926 by the Rawson-MacMillan Sub-Arctic Expedition for Field Museum.

† Includes 0.05 per cent Cl and 0.11 per cent rare earths.

23. Pink granite gneiss, Great Caribou Island, Battle Harbor. Percentages: oligoclase 30, microcline 30, orthoclase 6, quartz 10, biotite 10, hornblende 3, titanite 3, and magnetite 2; accessory apatite, pyrite, zircon, garnet, and traces of many kinds of secondary minerals. R. B. Ellestad, analyst.

24. Pinkish gray, gneissoid chlorite granite, Assizes Island, Assizes Harbor. Percentages: microcline and orthoclase 45, oligoclase 30, quartz 10, and chlorite after biotite 10; accessory magnetite, titanite, apatite, and traces of secondary minerals. R. B. Ellestad, analyst.

25. Pink granite, Lady Bight. Percentages: oligoclase 40, microcline and orthoclase 38, quartz 15, biotite 2, epidote 1, titanite 1, and magnetite 1; accessory muscovite, zircon, apatite, pyrite, and traces of secondary minerals. R. B. Ellestad, analyst.

26. Brownish-red granite, Merrifield Bay. Percentages: albite 30, perthite 30, microcline 2, quartz 20, hornblende 10, and magnetite 4; accessory apatite, zircon, and secondary hematite and traces of others. R. B. Ellestad, analyst.

27. Coarse pink granite, west side of Alliuk Bight. Percentages: perthite and orthoclase 65, oligoclase 6, quartz 7, biotite 15, and hornblende 5; accessory apatite, magnetite, titanite, pyrite, and traces of secondary minerals. T. Kameda, analyst.

28. Gray gneissic granite, Pigeon Island, Indian Harbor. Percentages: microcline and orthoclase 38, oligoclase 33, quartz 15, biotite 5, and hornblende 3; accessory apatite, magnetite, titanite, zircon, and traces of secondary minerals. T. Kameda, analyst.

29. Light-brownish granite, allanite aplite dike, Port Manvers. Percentages: microcline 40, albite 30, quartz 25, allanite 1, biotite 1, magnetite 1, and chlorite 1; accessory zircon, apatite, and traces of secondary minerals. R. B. Ellestad, analyst.

TABLE 5

ANALYSES OF ROCKS NORTH OF LAKE WINNIPEG

	30	31	32	33	34	35	36	37	38	39
SiO_2	74.26	56.91	72.87	74.14	76.47	72.34	64.33	71.22	74.13	75.70
Al_2O_3	13.58	17.67	13.58	14.76	12.64	13.91	17.42	15.92	14.19	13.35
Fe_2O_3	0.39	1.63	0.41	0.81	0.11	0.58	tr.	0.78	0.34	0.39
FeO	1.18	5.30	1.38	0.66	1.49	1.97	3.05	0.75	0.71	0.80
MgO	0.41	4.55	0.67	0.39	0.22	0.67	2.72	0.63	0.62	0.39
CaO	1.15	7.15	3.32	0.66	0.90	1.51	3.86	2.84	0.33	0.49
Na_2O	3.24	3.12	2.81	3.00	3.61	3.61	3.19	5.54	3.91	3.01
K_2O	4.72	1.25	3.58	5.40	3.71	4.11	4.34	1.61	4.94	5.31
H_2O+	0.35	1.33	0.36	0.20	0.28	0.41	0.86	0.34	0.61	0.52
H_2O-	0.03	0.06	0.04	0.10	0.03	0.03	0.12	0.05	0.04	0.01
CO_2	0.05	.....	0.47	.....	0.12	0.10	.....	.....	0.01	.....
TiO_2	0.23	0.67	0.26	tr.	0.16	0.33	0.40	0.16	0.13	0.08
ZrO_2	none	.....	.....	.....	.....	.....	0.12	.....	.....	.....
P_2O_5	0.28	.....	0.33	.....	0.15	0.34	0.12	0.07	0.07	0.04
S	tr.	.....	.....	.....	.....	.....	0.07	.....	.....	.....
MnO	0.03	.....	0.04	.....	0.03	0.05	0.05	0.03	0.01	0.02
BaO	0.07	.....	.....	.....	.....	.....	0.11	.....	.....	.....
Total	99.97	99.64	100.12	100.12	99.92	99.96	100.76	99.94	100.04	100.11
C.I.P.W.	I.4.1.3 Liparose	II.4.4.4 Bandose	I.4.3.3 Amiatose	I.4.1.3 Liparose	I.3.1.3 Alaskose	I.4.2.3 Toscanose	II.4.3.3 Harzose	I.4.2.4 Lassenose	I.4.1.3 Liparose	I.3.1.3 Alaskose
Johannsen	227 Granodiorite	228 Tonalite	127 Leucogranodiorite	126 Leucogranite	126 Leucogranite	226 Granite	227 Granodiorite	227 Granodiorite	126 Leucogranite	126 Leucogranite

30. Pinkish-gray granite, Red Sucker Lake, collected by J. F. Wright. Percentages: oligoclase 35, microcline 22, orthoclase and perthite 5, quartz 28, biotite 6, and magnetite 2; apatite and traces of secondary minerals. T. Kameda, analyst.

31. Dark-gray quartz diorite, north of Fay Lake, Kississing Lake area, collected by H. J. Fraser. Percentages: basic andesine 55, quartz 15, hornblende 20, biotite 6, and epidote 1; accessory apatite, magnetite, zircon, and traces of secondary minerals. R. B. Ellestad, analyst:

32. Pink, slightly gneissoid granite sill in Kississing Lake area, on Sheritt-Gordon property, collected by J. F. Wright. Percentages: andesine 32, microcline 20, orthoclase 6, quartz 35, augite 2, hornblende 1, biotite 1, and titanite 1; accessory apatite, zircon, and traces of secondary minerals. T. Kameda, analyst.

33. Pink granite, probably older than No. 32, central south bay of Kississing Lake, collected by H. J. Fraser. Percentages: microcline and perthite 35, oligoclase-albite 30, quartz 30, biotite 2, and garnet 2; accessory zircon, pyrite, and secondary sericite, chlorite, and hematite. R. B. Ellestad, analyst.

34. Pink gneissoid granite of large batholith from northeast of Kississing Lake to Churchill River, collected by J. F. Wright. Percentages: quartz 35, oligoclase 25, microcline 25, orthoclase 10, biotite 2, and magnetite 1; allanite (?) and traces of secondary minerals. T. Kameda, analyst.

35. Pinkish-gray gneissic granite of large Kaminis batholith, southeast of Kisseynew Lake, collected by J. F. Wright. Percentages: quartz 35, oligoclase 28, microcline 20, orthoclase and perthite 11, and biotite 3; small amounts of hornblende, apatite, and leucoxene. T. Kameda, analyst.

36. Pink porphyritic granodiorite, Reindeer Lake, collected and analyzed by George Ward. This rock resembles the average—Table 6, No. 4. Tested for Cr_2O_3 but none found. Biotite is green and contains 20.18 per cent iron oxide calculated as Fe_2O_3. Percentages: oligoclase 40, microcline and orthoclase 15, quartz 25, biotite 10, magnetite 3, and titanite 2; accessory zircon, apatite, and secondary sericite, chlorite, and hematite.

37. Pink granite, Gods Lake, Manitoba, collected by H. S. Hicks. Percentages: albite-oligoclase 55, microcline 10, quartz 25, hornblende 3, biotite 2, and epidote 2; accessory magnetite, apatite, titanite, and zircon, and traces of various secondary minerals. Lynn Gardiner, analyst.

38. Red granite, south shore of Winter Lake, latitude 64°30′ N, collected by H. S. Hicks. Percentages: orthoclase 25, microcline 10, oligoclase 25, quartz 35, and chlorite 2; miscellaneous alteration products. Emil Fattu, student analyst.

39. Red granite near contact of paragneiss, latitude 65°45′ N., longitude 112°45′ W., collected by H. S. Hicks. Percentages: microcline 35, oligoclase 25, quartz 35, biotite 1, muscovite 1, and chlorite 2; traces of magnetite and miscellaneous alteration products. O. Alstad, student analyst.

THE COMPOSITION OF THE CANADIAN SHIELD

1. *A grand average.*—The chemical data on the Canadian Shield have largely increased since the work of Clarke and Washington.[7] They used ninety-nine analyses for the area of East Canada, the Shield. There are now about five hundred analyses for the igneous rocks of the Shield. It was thought that perhaps the increased data would show important differences from the average they obtained (see Table 6, cols. 1 and 2). Probably, as they noted, the alkalies were too high in the first estimate because of the several analyses of alkalic rocks in the Haliburton district.[8]

2. *An average by formations.*—It is easily possible to criticize the methods used by Clarke and Washington in making their averages, but there are very few large regions in which the data permit any other method at present. Sederholm has presented a discussion of the rocks of Finland with data on the areas and compositions of nine different formations.[9] He criticized the use of many analyses of interesting rocks of small volume. And his calculation for Finland used some analyses of sediments as well as of igneous rocks. He suggested "separating the effusive and plutonic rocks" to see if they differ widely in composition. Several of these suggestions have been carefully considered, and preliminary calculations for Canada give the results of Table 6.

Column 3 of Table 6 makes allowance for the areas of different rocks in the Shield. It has not seemed practicable on the basis of published maps to distinguish very many formations. After several combinations were tried, an estimate was made (1) of granites, gneisses, and related batholith rocks; (2) of flows and small intrusives; and (3) of sediments of the pre-Cambrian. The areas of these were estimated from something over twenty of the best maps of the Shield areas. Various reports also state the approximate proportions of granite and gneiss in large areas. The estimates range from about 50 to 98 per cent granite and related rocks, and the average is 70 per cent. This is believed to be very conservative. In the first place, as Sederholm maintains, few Shield areas have over

[7] *Op. cit.*

[8] Noted by J. J. Sederholm, "The Average Composition of the Earth's Crust in Finland," *Bull. comm. géol. Finl.*, No. 70 (1925), p. 14.

[9] *Ibid.*, pp. 12–15.

10 per cent of basic rocks, these being in flows and less abundant in relative volumes than their areas indicate. Granites are unduly subordinated in published maps, also, because few areas in a large granite batholith are selected for mapping—economic deposits are more likely to be found where rocks show some variety. On the strength of this reasoning it is believed that column 3, with its slightly greater silica than columns 1 and 2, is an approach to a more correct value.

The calculation of average flows and small intrusives as distinct from batholiths gave a noteworthy result. The flows are more basic, as expected, but the difference in silica content is only about 2 per cent.

It is noteworthy, also, that the inclusion of sediments in the calculations adds $CaCO_3$ and normative alumina to the result. The amounts are not large, however, and, if the lime and alumina are calculated back to anorthite, the rock is a tonalose, corresponding in classification to the other averages and estimates.

3. *An average by areas.*—The distribution of the rocks previously analyzed is very striking (Fig. 1). Evidently most of the rocks analyzed are those outcropping in districts where human industry and habitation have made them accessible. As a consequence nearly all the specimens are from south of the fiftieth degree of latitude. Of 500 analyses, only 37 are from rocks north of the latitude of Winnipeg, Nipigon, and the Gulf of St. Lawrence; and only 6 are from the great area between latitudes 57° and 68°, which is about half the Shield.

The analyses here given, with a few already published from the same laboratory,[10] approximately double the chemical data for the area north of latitude 50°, and give the only data for that half of the Shield farthest north. It is therefore well to note some of the features that may be indicated by further analyses of rocks in the area.

In logical continuation of methods of estimating an average, the Shield was divided into a series of areas (by parallels of latitude), and the analyses of rocks in each area were averaged. Then the averages were given weight according to the sizes of the areas they represent. For some small areas there are many analyses to average,

[10] Grout, *op. cit.*, p. 807. The rocks, analyses of which are there tabulated, have modes indicating granodiorites and sodaclase-granites.

TABLE 6

PRELIMINARY ESTIMATES OF THE COMPOSITION OF THE EARTH'S CRUST IN THE CANADIAN SHIELD AND CERTAIN AREAS OF IT

	General Averages				Sudbury District		
	1	2	3	4	5	6	7
SiO_2	52.74	57.71	57.76	63.08	61.23	59.48	57.24
Al_2O_3	16.40	15.85	16.52	16.75	14.69	14.53	14.44
Fe_2O_3	4.59	2.87	3.16	2.38	1.68	3.04	1.69
FeO	5.84	5.27	4.72	2.91	5.81	6.71	7.62
MgO	3.27	3.25	2.75	1.78	3.58	3.22	4.09
CaO	5.30	4.76	4.07	4.07	4.99	5.16	6.11
Na_2O	4.89	3.51	3.68	3.64	3.05	2.96	2.56
K_2O	2.65	2.49	2.82	3.07	2.62	2.13	2.19
H_2O+	1.09	1.50	1.59+	0.79	1.30	1.58	1.19
H_2O-	.....	0.05	0.18	.....	.....	0.01	0.09
CO_2	.....	0.85	1.38	0.39	0.14	0.16	0.70
TiO_2	2.20	0.93	1.37	0.81	0.90	0.20	0.96
P_2O_5	0.21	0.16	0.21	0.22	0.34	0.03	0.16
S	.....	0.14	0.20±	0.12	0.08	0.60	0.54
MnO	0.17	0.05	0.08	0.02	0.10	0.02	0.09
BaO	.....	0.02	.....	0.02	.....	0.01	0.03
Inclusive	0.65	0.12	.....	.....	.....	0.17	0.30
Total	100.00	99.53	100.49	100.05	100.51	100.01	100.00
C.I.P.W. Symbol	II.5.2.4	II.4.3.4	II.4.2.4	II.4.3.4	II.4.3.4	II.4.3.4	II.4.3.4
C.I.P.W. Class	Akerose	Tonalose	Dacose	Tonalose	Tonalose	Tonalose	Tonalose

1. Average by Clarke and Washington for igneous rocks of East Canada (99 analyses).

2. Average by Grout for igneous rocks of Canadian Shield (494 analyses).

3. Average by Grout calculated to include 70 per cent of average batholithic rocks (209 analyses), 17 per cent of flows and small intrusives (149 analyses), and 13 per cent of sediments of the Shield (analyses rather roughly estimated from scattered data). The group of analyses of the Sudbury district is omitted here (see cols. 5, 6, and 7) but makes little difference.

4. Average by Grout using analyses by groups in different areas and allowing weight according to areas.

5. Average by Burrows and Rickaby of recent good analyses of the Sudbury nickel eruptive reported by Coleman, Moore, and Walker, *35th Rept., Ontario Dept. Mines*, Part III (1929), p. 27.

6. Average of other analyses of the Sudbury nickel eruptive.

7. Average of analyses of igneous rocks in the Sudbury district outside of the nickel eruptive.

but for the large north half of the Shield only a few analyses. These have been selected by field geologists to represent large bodies and are accordingly mostly granite batholiths. Possibly this method results in assigning to too large a part of the area a granitic composition, but it is almost certain that the other methods assign such a granitic composition to too small a fraction. The result of the calculation is therefore added as column 4, along with the others. This is perhaps a granodiorite in composition, and it seems more than likely that the average rock of the Shield is closer to this composition than to the early average of 99 analyses. It is noteworthy, however, that even this most silicic estimate still falls in the class, tonalose, along with the other recent estimates.

4. *Comparison of the whole area and a part.*—In contrast to the estimate of the composition of the large area by a large number of analyses, it is noteworthy that some smaller districts have been well studied, and analyses of the rocks are numerous. It seemed that there might be enough analyses to give a fair comparison of the district with the whole region. The Haliburton area, which comes to mind, is not fairly represented. Sederholm noted that, although the area is mainly granite, there were 16 analyses of nephelite syenite and only 2 analyses of granite.[11] The Sudbury district, on the other hand, has had a particularly full study. An average for the "nickel eruptive" has been estimated from the best data; other data for the same mass are about as numerous, and there are analyses of other rocks in the same district so that a total of 136 analyses are at hand. Each of the three groups and the grand total are much like the average rock of the whole Shield—all are probably to be classified as tonalose in the C.I.P.W. system.

5. *Comparison with the outlying districts.*—Clarke and Washington compare the district of East Canada with the more alkalic Greenland district, and the extensions of the Shield area in New England and the Algonkian districts. The different methods of estimating the average used in this paper produce greater differences in the result than the differences between the main area and its extensions, or between the total area and a well-studied district like that near Sudbury.

[11] *Op. cit.*, p. 14.

SOME NEW VARIATION DIAGRAMS FOR GROUPS OF IGNEOUS ROCKS

ESPER S. LARSEN
Harvard University

ABSTRACT

A modified variation diagram for plotting groups of chemical analyses of related igneous rocks is proposed. The major constituents—SiO_2, Al_2O_3, total iron +Mn as FeO, MgO, CaO + BaO + SrO, Na_2O, and K_2O—are adjusted so that their sum is 100. The position of the rock is determined by the average of the major oxides as one-third $SiO_2 + K_2O - FeO - MgO - CaO$. Relatively uniform variation diagrams result, and they characterize the rocks of the province.

In a triangular diagram two groups of normative minerals are plotted as two points and are joined by a line. For one group normative or-ab-an are used. Feldspathoids are calculated to feldspar by adding SiO_2, and they are then added to the feldspar, and the total adjusted to 100. For the other group total feldspar (with feldspathoids adjusted to feldspar added), femic constituents (olivine adjusted to pyroxene), and quartz or deficient SiO_2 are plotted. In these plots the positions of the lines, their slopes and lengths, are all significant.

Plots of analyses from a petrographic province show a systematic arrangement of lines and points but with some erratic analyses. They also bring out systematic differences between petrographic provinces.

The plotted points for most petrographic provinces of the lime-alkalic series begin abruptly with basalts (47 per cent SiO_2) and end abruptly with rhyolites (77 per cent SiO_2). In such provinces, especially for lava fields, the total amount of normative feldspar in most rocks is near 65 per cent and the amount of albite in the feldspar is about 47 per cent.

INTRODUCTION

Variation diagrams are in some disrepute at the present time, and the statement is commonly made that a petrographer can learn as much by a careful comparison of chemical analyses as by the construction of a variation diagram. This may be true where the members of a small group of analyses are compared, but where many analyses from a petrographic province are compared for the purpose of learning in detail the laws of variation in the province and the erratic compositions of some of the rocks of the province, and where the rocks of a petrographic province are compared with those of another province, a suitable variation digram is nearly indispensable.

In the course of the field and laboratory study of a number of petrographic provinces in the western United States, ordinary variation diagrams were constructed by plotting the other oxides against

SiO_2. For the Tertiary lavas of the San Juan Mountains of Colorado, which range from rhyolite to basalt, and for the rocks of the Jurassic batholith of southern California, which range from granite to gabbro, most of the points fall near a fairly smooth curve. However, for some of the analyses the points would fit the curves much better if all the points for that analysis were shifted some distance to the right or left—to lower or higher silica. For rocks belonging to alkalic provinces, such as the Highwood Mountains of Montana, the points do not fit well on a curve when the oxides are plotted against silica, since the silica varies but little, though erratically, in such rocks.

THE NEW VARIATION DIAGRAMS

In petrographic provinces where the rocks range from basalt or gabbro to rhyolite or granite, the silica increases rather regularly, and in most batholiths the earliest intrusions were low in silica and later intrusions were progressively more siliceous. There is some justification, therefore, with such rocks for plotting the other oxides against silica. However, potash increases, and lime, total iron, and magnesia decrease about as regularly as silica changes. Moreover, it is about as likely that there is an analytical error in the determination of silica as of the other oxides, and magmas are as likely to be erratic in their silica content, through contamination or some other process, as in their other oxides.

After making many plots, it seems best to the author to determine the position of the rock on the basis of all its variable major constituents, which are SiO_2, CaO, MgO, total iron, and K_2O. Alumina is erratic and does not have a uniform slope; soda is nearly constant. The variation curves (Figs. 2–5) show that the range in percentages —from rhyolite to basalt—for all the constituents except SiO_2 is about the same, and the latter has about three times this range. In the plots advocated in this paper, the position of the analysis is determined by the sum of one-third SiO_2 and K_2O minus the sum of the MgO, CaO, and total iron calculated as FeO, or one-third $SiO_2 + K_2O - MgO - CaO - FeO$.

To make the calculation, MnO is added to FeO, BaO and SrO are added to CaO, and the major oxides, SiO_2, Al_2O_3, FeO+nine-tenths of Fe_2O_3, MgO, CaO, K_2O, and Na_2O are adjusted so that their sum

is 100. These adjusted values are used to determine the position of the analyses, which may be either positive or negative; and they are the abscissa values plotted on the diagram.

To illustrate the method, the calculations for a dike rock from the Highwood Mountains, Montana, are given in Table 1.

TABLE 1

EXAMPLE OF CALCULATIONS FOR DETERMINING ABSCISSA POSITION IN VARIATION DIAGRAMS

	1	2	3
SiO_2	49.26	49.3	51.2
Al_2O_3	13.64	13.6	14.2
Fe_2O_3	1.72		
FeO	7.76	9.4	9.8
MnO	0.12		
MgO	8.31	8.3	8.6
CaO	8.42	8.7	9.0
Na_2O	1.90	1.9	2.0
K_2O	5.02	5.0	5.2
H_2O+	1.21	.....	.....
H_2O-	0.32	.....	.....
TiO_2	1.11	.....	.....
P_2O_5	0.75	.....	.....
BaO	0.22 to	.....	.....
SrO	0.07 CaO		
Total	99.83	96.2	100.0

Position one-third $SiO_2+K_2O-MgO-CaO-FeO$

$17.1+5.2-8.6-9.0-9.8=-5.1$

Column 1 gives the analysis, column 2 the major oxides after combining some, and column 3 the major oxides adjusted to add to 100.

These diagrams were first devised for rocks of the lime-alkalic series, but they apply as well to alkalic rocks, since the main oxides vary in about the same way in both series.

Since in nearly every petrographic province the variation in the rocks and the order of intrusion for stocks and larger intrusive complexes are from rocks rich in femags and calcic feldspar to those low in these constituents,[1] reasonable positions for the rocks of a province are the sums of CaO, MgO, and FeO. Figure 1 shows the

[1] N. L. Bowen, "Recent High Temperature Research on Silicates and Its Significance in Igneous Geology," *Amer. Jour. Sci.*, Vol. XXXIII (5th ser., 1937), pp. 1–21.

relation between the positions of several groups of rocks for the two methods of calculation. For the lime-alkalic rock the points fall near a straight line, and plots by the two methods differ chiefly in scale. For the potash-rich rocks of the Highwood Mountains of

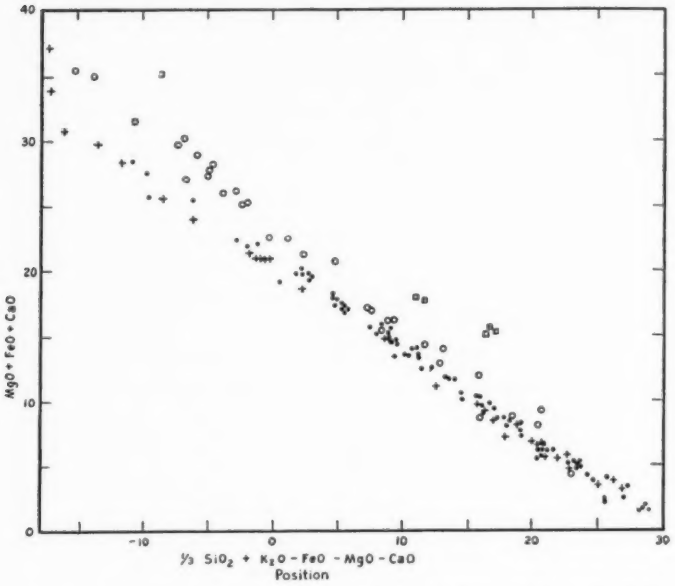


FIG. 1.—The relation between the values of $\frac{1}{3}$ $SiO_2+K_2O-MgO-FeO-CaO$ and $MgO+FeO+CaO$ for several petrographic provinces. San Juan Mountains, Colorado—dots; batholith of southern California—crosses; Highwood Mountains, Montana—circles; and the Crazy Mountains, Montana—squares.

Montana the points are more scattered, and a less satisfactory straight line can be drawn to represent them. As compared with the lime-alkalic series, the two lines lie near together at the femic-poor end but are separated considerably at the femic-rich end. For the rocks of the highly potash-rich province of the Leucite Hills, Wyoming, the line is some distance from that for the lime-alkalic rocks.

Provinces of ultrafemic rocks do not yield satisfactory curves on any chemical variation diagram with which the author is familiar.

SOME VARIATION DIAGRAMS

In Figures 2 and 3, analyses from the volcanic provinces of the San Juan Mountains of Colorado and the Modoc area of northern California are plotted, and in Figure 4 those from the Jurassic batholith of southern California. These three are lime-alkalic provinces. In each of the provinces most of the oxides fall near rather smooth curves—almost within the limit of probable error of the analyses. A few of the analyses fail to fit the curves, but they are unreliable analyses or the rocks they represent failed to follow the normal course of differentiation. In some cases they represent imperfect sampling of the rock for analysis or an incorrect analysis. A number of analyses that failed to fit the curves and that showed no reason for this failure in the microscopic study were repeated and about half the new analyses fit the curves satisfactorily.

Figure 5 is a plot of analyses from the Highwood Mountains of Montana, a province characterized by shonkinites and nepheline syenites in the granular rocks, and of femic rocks, with leucite, analcime, and pseudoleucite and syenite porphyries in the flows and dikes. In this plot the oxides do not fall so near to smooth curves as they do in the lime-alkalic series, yet they show some tendency to a regular variation.

In Figure 6 curves of variation for five lime-alkalic provinces are plotted—the lava fields of the San Juan Mountains of Colorado; Modoc, California; Katmai, Alaska; San Francisco Mountains of Arizona; and the granitic rocks of southern California. The curves for these five provinces fall fairly close together but with differences that are much greater than the probable error of the curves.

As compared with the average of the five curves, the rocks from the San Juan Mountains, Colorado, are high in K_2O, high in FeO and MgO for the femic rocks, high in CaO for salic rocks, and low in SiO_2; those from Modoc, California, are about average for all the constituents; those from the San Francisco Mountains, Arizona, are high in Na_2O and for the salic rock low in CaO; those from Katmai, Alaska, are high in SiO_2 and low in K_2O and FeO; those from the batholith of southern California are low in Na_2O, K_2O, and FeO, and, for the femic rocks, high in CaO.

In Figure 6 are also plotted the rocks of the alkalic provinces of

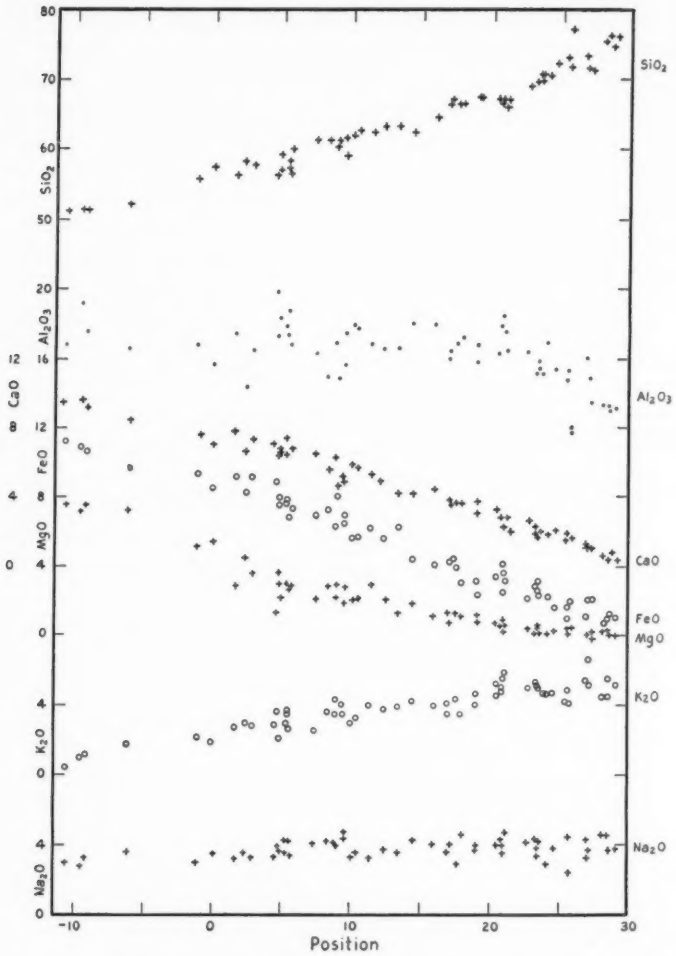


FIG. 2.—Variation diagram for the lavas of the San Juan Mountains, Colorado. Abscissa $\frac{1}{3}$ $SiO_2+K_2O-FeO-MgO-CaO$.

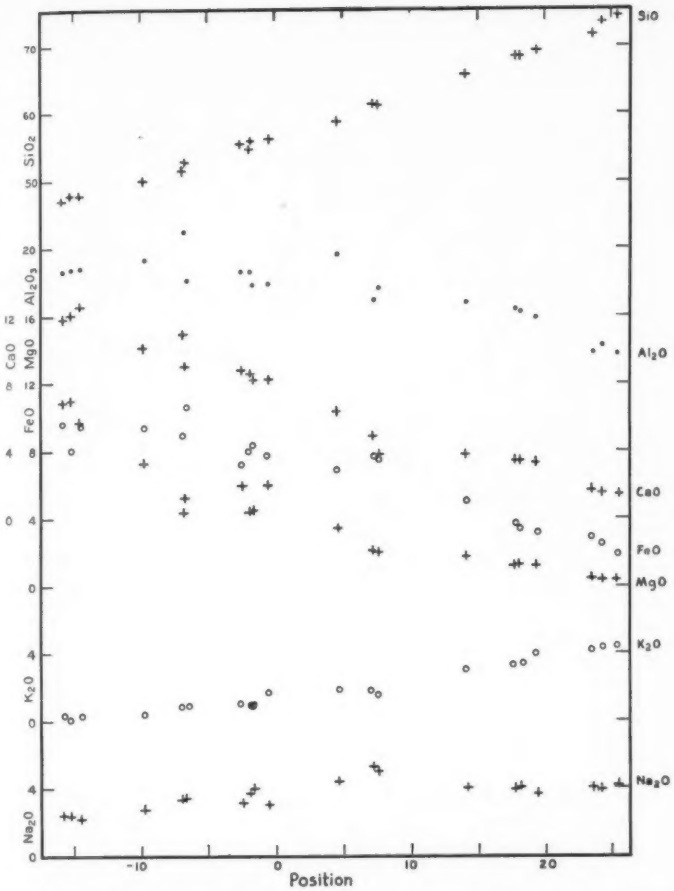


FIG. 3.—Variation diagram for the lavas of the Modoc area of California. Abscissa $\frac{1}{4}$ $SiO_2+K_2O-FeO-MgO-CaO$.

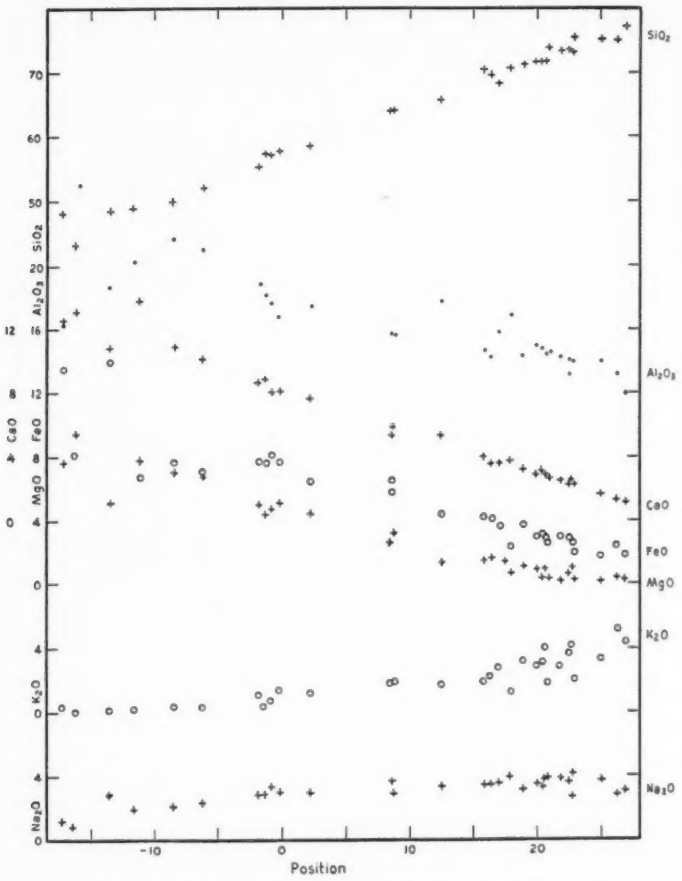


FIG. 4.—Variation diagram for the rocks of the Jurassic batholith of southern California. Abscissa $\frac{1}{3}$ $SiO_2+K_2O-FeO-MgO-CaO$.

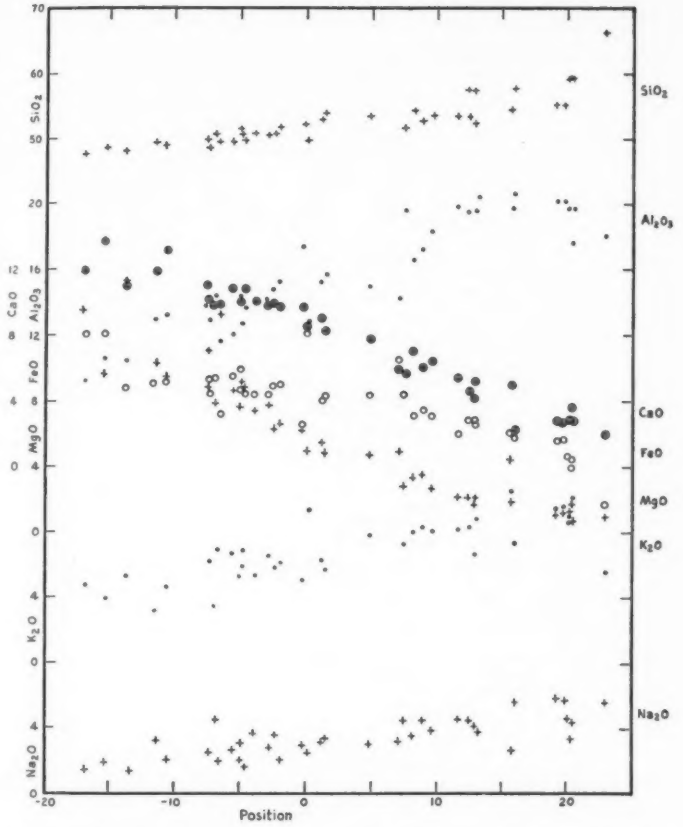


FIG. 5.—Variation diagram of the rocks of the Highwood Mountains, Montana. Abscissa $\frac{1}{3}$ $SiO_2+K_2O-FeO-MgO-CaO$.

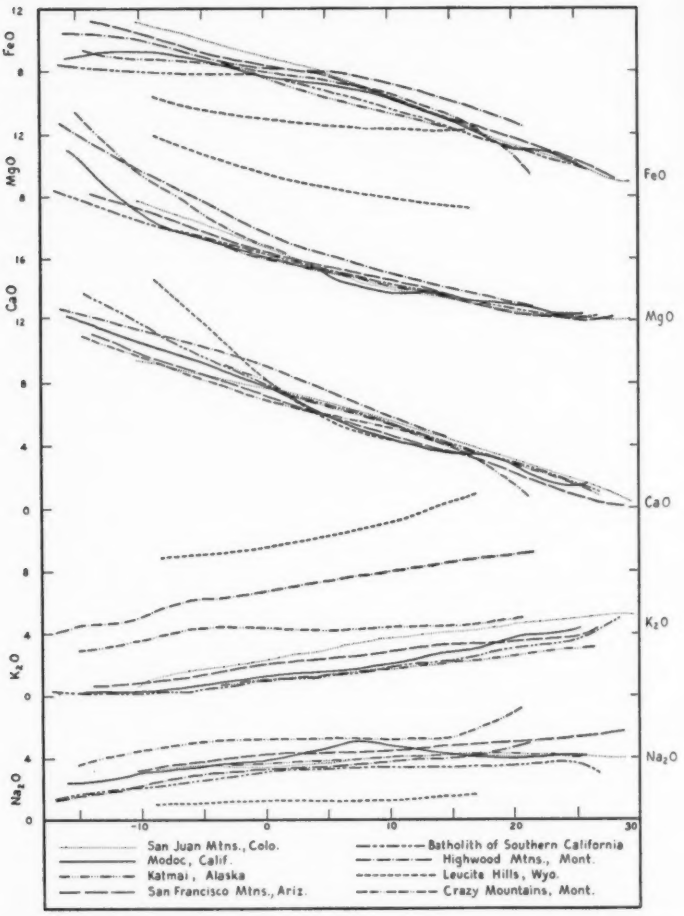


FIG. 6.—Variation curves for a number of petrographic provinces to show the differences in characters of the provinces.

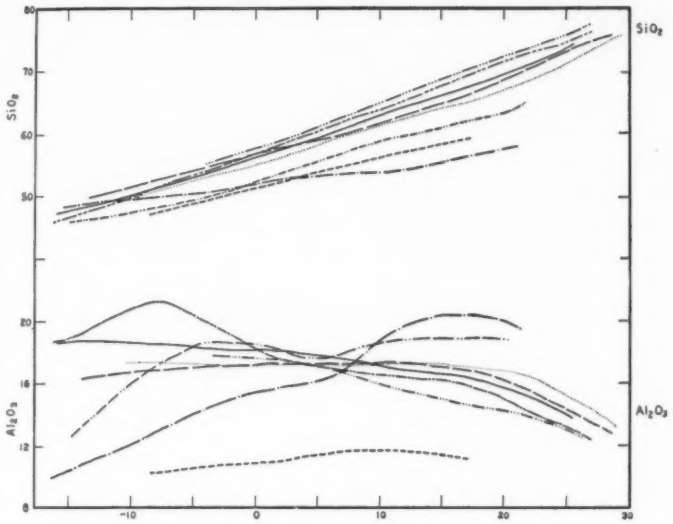


FIG. 6—*Continued*

the Crazy Mountains, Montana,[2] the Highwood Mountains, Montana, and the Leucite Hills, Wyoming. As compared with the lime-alkalic rocks, the rocks of the Highwood Mountains have about the same SiO_2 content at the femic end but have much less SiO_2 at the salic end; they are very low in Al_2O_3 at the femic end and high at the salic end; they are somewhat high in FeO, MgO, and CaO, are high in K_2O, and a little low in Na_2O.

The Crazy Mountains are only 80 miles south of the Highwood Mountains, the rocks of the two areas are of about the same age, and are very similar, ranging from shonkinite to syenite and nepheline syenite in both areas, and there are similar rocks in the intervening area. Yet the rocks of the Crazy Mountains are more like the lime-alkalic rocks than are those of the Highwood Mountains, and they are high in soda.

The rocks of the Leucite Hills are very rich in potash. The diagrams show them to be especially low in Na_2O, FeO, Al_2O_3, and SiO_2, and high in K_2O and MgO.

[2] J. E. Wolff. Manuscript kindly furnished by Dr. Wolff.

TRIANGULAR DIAGRAMS

Triangular diagrams of various kinds were tried, and the most instructive of these were two based on a modification of the norms of the rocks. For the first plot the normative feldspar of the rock (in silica-deficient rocks feldspathoids are calculated to feldspar) is calculated to 100 per cent and or, ab, and an are plotted. To do this, the normative nepheline is multiplied by 1.845 and added to the albite, and leucite is multiplied by 1.275 and added to orthoclase.

For the second plot the normative quartz, feldspar, and femic minerals are calculated to 100 per cent and plotted. Where there is olivine, it is multiplied by 1.43 for forsterite and 1.29 for fayalite to convert them to pyroxene. For most olivine, if in moderate amount, the factor 1.40 is sufficiently accurate. If there is nepheline and leucite, they are calculated to feldspar as described above, before including in the feldspar. The amount of SiO_2 added to olivine, nepheline, and leucite to yield pyroxene and feldspar is the SiO_2 deficiency. Where there is deficient SiO_2, the sum of the feldspar and femic minerals is 100 per cent. SiO_2 is placed on the lower left of the diagram, feldspar on the lower right, and femic minerals at the top. To plot deficient SiO_2, the base of the diagram is extended to the right and a parallel line at the upper apex of the diagram is drawn. In this area beyond the triangle the position along a line parallel to the right side of the triangle represents the proportions of feldspar and femic minerals and the distance of this line from the edge of the triangle represents the deficiency in SiO_2.

A calculation for these plots for a dike rock from the Highwood Mountains, Montana, is shown in Table 2, and below it appear the feldspar-femic-silica plot values.

To show as many of the characters of the rocks as possible, these two groups of values are plotted together on a triangular diagram, and the two points for each analysis are joined by a line. The resulting plot shows the Na_2O, K_2O, and CaO of the feldspar and feldspathoids, the oversaturation or undersaturation of the rock, and the proportion of femic minerals in the rock.

Plots of this kind for rocks from the San Juan Mountains of Colorado, Modoc lava fields of California, San Francisco Mountains of Arizona, the batholith of southern California, and the Highwood

Mountains of Montana are shown in Figures 7–10. The character of the province is shown by the slopes and lengths of the joining lines as well as by their positions, and in every province the lines show some systematic features but with a few erratic analyses.

TABLE 2

EXAMPLE OF CALCULATIONS FOR DETERMINING LOCATION OF POINTS ON A TRIANGULAR DIAGRAM FOR A SILICA-DEFICIENT ROCK

	Norm	Calculated to Saturated Minerals		Silica Deficiency
or	29.47	29.5	47.5	
ab	16.24	22.0	35.5	
ne	3.12	.....	.....	2.0
an	10.48	10.5	16.9	
Sum	.....	62.0	100.0	
di	17.49	17.5	.....	
ol	14.74	20.6	.....	5.9
mg	2.55	2.6	.....	
il	1.98	1.9	.....	
ap	2.35	2.3	.....	
Fem	39.11	44.9	.....	7.9

		To 100 Per Cent
Feldspar	62.0	58.0
Femic	44.9	42.0
	106.9	.....
Silica deficiency	7.9	7.9

In the plot (Fig. 7) of the rocks from the lavas of the San Juan Mountains, Colorado, the lines slope rather gently down to the right. In the plot (Fig. 8) of the rocks from Modoc lavas, California, the lines slope more steeply to the right and are shorter than those of the plot of the San Juan rocks. In the plot (Fig. 9) for the rocks from the southern California batholith, the lines are much like those for the Modoc rocks, but they are somewhat steeper and displaced

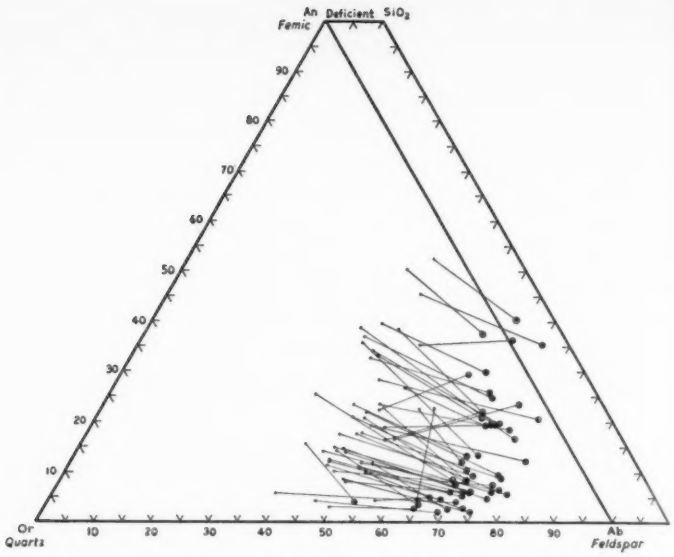


FIG. 7.—Triangular diagram for the lavas of the San Juan Mountains, Colorado. Dots are or-ab-an; circles are quartz (or deficient SiO_2)-feldspar-femic.

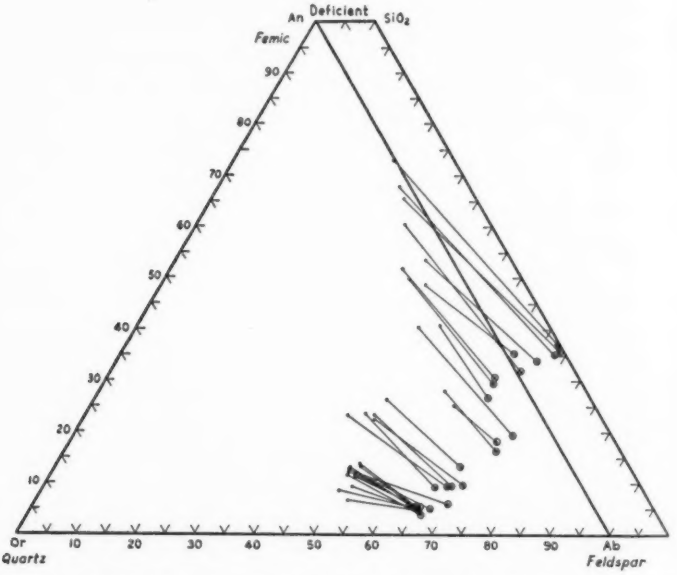


FIG. 8.—Triangular diagram for the lavas of the Modoc area, California. Dots are or-ab-an; circles are quartz (or deficient SiO_2)-feldspar-femic.

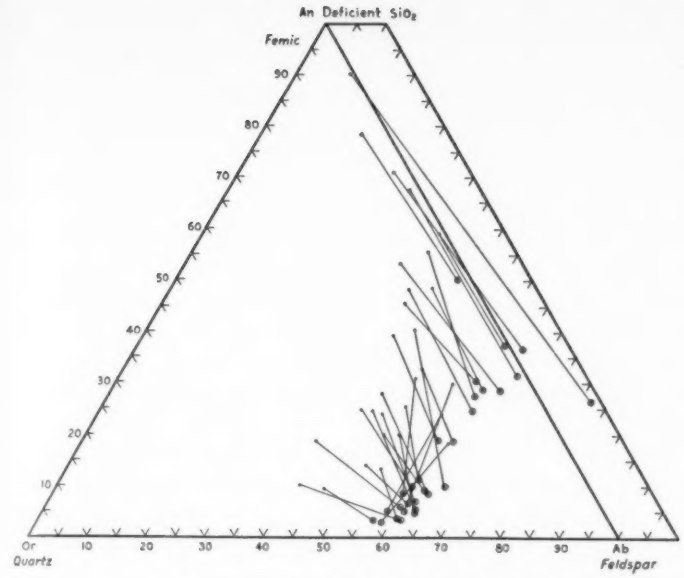


FIG. 9.—Triangular diagram for the rocks of the batholith of southern California. Dots are or-ab-an; circles are quartz (or deficient SiO_2)-feldspar-femic.

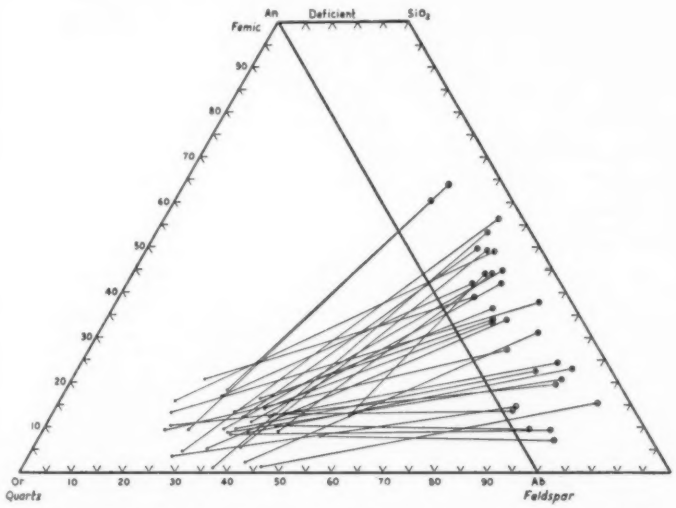


FIG. 10.—Triangular diagram for the rocks of the Highwood Mountains, Montana. Dots are or-ab-an; circles are quartz (or deficient SiO_2)-feldspar-femic.

to the left. In the plot (Fig. 10) for the rocks from the alkalic province of the Highwood Mountains, Montana, the lines dip gently down to the left and are very long.

SOME GENERAL FEATURES

For the lime-alkalic rocks the normative albite does not vary greatly from 47 per cent of the normative feldspar except in the extreme rhyolites and extreme basalts where the albite content is low. In the basaltic and gabbroic rocks the soda is chiefly in the plagioclase, and in the rhyolitic and granitic rocks it is chiefly in the alkalic feldspar—sanidine, microperthite, and groundmass feldspar.

For all the lime-alkalic rocks the total amount of feldspar is rather uniform except in the extreme rocks and is about 65 per cent. This means that the sum of the quartz and femic minerals is nearly constant. In the basaltic end it is chiefly femic minerals and in the rhyolitic rocks it is chiefly in the form of free silica.

In all the volcanic provinces of lime-alkalic rocks studied there seems to be a definite beginning for the curves at a typical basalt and a rather abrupt ending at a rhyolite with about 77 per cent SiO_2. In some of the provinces, as Modoc, California, and San Juan, Colorado, there are several rocks of very different ages that fall near the ends of the diagrams. The rocks near the silica-rich end are for the most part obsidians, but some are felsites and some are porphyritic rocks with phenocrysts of sanidine or of quartz and sanidine.

DIE ZUSTANDSGRÖSSEN DES SANTORINAUSBRUCHS 1925–26: EIN BEITRAG ZUR THEORIE ANDESITISCHER VULKANAUSBRÜCHE

FERDINAND VON WOLFF
Universität Halle

AUSZUG

Stoff, Temperatur, und Druck an der Schlotmündung sind die wichtigsten Zustandsgrössen eines Vulkanausbruchs. Der feste und flüssige Stoff bleibt während der Förderung volumenkonstant, der gas- oder dampfförmige unterliegt der adiabatischen Ausdehnung und Abkühlung. Für den Santorinausbruch 1925–26 liegen zahlreiche pyrometrische Temperaturmessungen der Lava an der Schlotmündung und Bestimmungen der Tagesförderungen von Lava vor, die die Ausflussgeschwindigkeiten der Lava aus dem Schlot mit bekanntem Durchmesser zu ermitteln gestatten. Mit Hilfe der Poiseuille'schen Formel ist hieraus die Viskosität der Lava zahlenmässig zu erfassen und den jeweils gemessenen Temperaturen zuzuordnen. Die Viskosität des Santorinmagmas entspricht etwa der gewisser technischer Silikatgläser. Die Morphologie vulkanischer Gebilde, wie Ströme, Staukuppen, Felsnadeln hängt von der stark temperaturabhängigen Viskosität ab. Es wird in einer Kurve die Beziehung Höhe: Basisdurchmesser der Staukuppen zur Viskosität dargestellt, die im plastischen Gebiet umbiegt und Anhaltepunkte für die Entstehungstemperaturen der Staugebilde herauslesen lässt.

Die Steighöhe der Eruptionswolke liefert mit dem in dieser Höhe herrschenden Dampfdruck und der Temperatur die Zustandsgrössen des Entspannungszustandes, das heisst das Ende der adiabatischen Ausdehnung und Abkühlung, denn der Dampf steigt solange auf, bis er sich mit der umgebenden Atmosphäre in ein Gleichgewicht gesetzt hat. Ist die Mündungstemperatur gegeben, so folgt nunmehr auch der Mündungsdruck aus den Adiabatengleichungen, damit ist auch die dritte Zustandsgrösse, die sich bisher der Bestimmung entzog, zahlenmässig erfasst. Die Wasserdämpfe treten aus der grössten Profilenge des Schlotes, die an der Schlotmündung liegt, mit Schallgeschwindigkeit aus. In diesem Fall wird das Verhältnis Mündungsdruck zum Herddruck gleich dem kritischen Druckverhältnis und eine Funktion des adiabatischen Exponenten. Mit dem kritischen Druckverhältnis und den Adiabatengleichungen ist mit den Zustandsgrössen der Mündung auch der Herddruck und die Herdtemperatur am Anfang des Schlotes zu gewinnen. Die Schallgeschwindigkeit im Wasserdampf bei der Mündungstemperatur liefert schliesslich noch den Wärmeinhalt der Masseneinheit an der Mündung und im Herd, ein ausgezeichnetes kalorisches Masz für die Intensität des Vulkanausbruchs. Die Differenz des Wärmeinhalts am Anfang und Ende der Ausbruchsperiode ergiebt den Erschöpfungszustand in Zahlen.

Zum Schluss werden die Zustandsgrössen des Sakura-jima, Pelé, Lassen Peak mit dem Santorinausbruch vergleichend gegenübergestellt.

EINLEITUNG

Der Zustand der Materie wird von drei Veränderlichen beherrscht, vom Stoff, Temperatur, und Druck. Den Stoff pflegt man als Konzentration X, die Temperatur mit T in absoluter Zählung, gerechnet von absoluten Nullpunkt, $-273°$, oder mit t in Celsiusgraden, den Druck mit p in kg/cm² oder in Atmosphären zu bezeichnen.

Bei andesitischen Ausbrüchen ist der Stoff, von geringfügigen Unterschieden abgesehen, gleich; höchsten mag das eine Magma gasreicher sein als das andere. Unterschiede im Ablauf der Ausbruchserscheinungen oder der Art der Förderprodukte, wie Lavaströme, Staukuppen, oder feste Felsnadeln u.s.w. sind weniger stofflich bedingt, sondern hängen im wesentlichen von den beiden anderen Zustandsgrössen Temperatur und Spannung oder Druck des aufdringenden Magmas ab.

Temperatur und Druck sind demnach die beiden Zustandsgrössen, die den Charakter eines Ausbruchs bestimmen.

Bei dem meist stürmischen Verlauf der Vulkanausbrüche sind Messungen vulkanischer Grössen gewöhnlich nur aus der Entfernung möglich. Von den beiden Zustandsgrössen ist die Temperatur noch am einfachsten mit Hilfe optischer Pyrometer zu messen, die bis zu 600° herab brauchbar sind. Dagegen ist der andere Faktor, der Druck, die Spannung des Magmas, durch unmittelbare Messung überhaupt nicht zu erfassen; er kann nur auf Umwegen durch Rechnung ermittelt werden. Leicht aus der Entfernung zu messen ist dagegen die Steighöhe der Eruptionswolke. Die Eruptionswolke steigt solange auf, bis die gespannten vulkanischen Gase und Dämpfe sich mit der Luft der Umgebung in ein Gleichgewicht gesetzt haben. Die Steighöhe liefert daher die Zustandsgrössen t_0 und p_0 des Entspannungszustandes. Ist nun die Temperatur an der Vulkanmündung durch Messung bekannt, so ist mit der adiabatischen Ausdehnung und Abkühlung die Mündungsspannung zu berechnen. Dies zu zeigen ist die Aufgabe der folgenden Untersuchung.

Von besonderer Bedeutung ist der erste wegbahnende Paroxysmus. Grade für diesen fehlen gewöhnlich zuverlässliche Daten.

Der vulkanische Ausbruch setzt meist plötzlich ein, seine wissenschaftliche Untersuchung beginnt gewöhnlich erst, wenn der Vulkan bereits einige Zeit tätig war. Andere vulkanische Grössen, z.B. die Ausflussgeschwindigkeit der Lava sind durch Eintragung des jeweiligen Standes der vorrückenden Lava von Zeit zu Zeit in die Karte und durch Ausmessen des Volumens zu gewinnen.

DER SANTORINAUSBRUCH 1925–26

Besonders günstig liegen die Verhältnisse für den jüngsten Ausbruch des ägäischen Santorinvulkans, weil sein Ausbruch 1925 von Anfang an durch eine deutsch-griechische Arbeitsgemeinschaft beobachtet und vermessen wurde. In dem Santorinwerk von H. Reck[1] ist das reiche Beobachtungsmaterial niedergelegt worden. Es erlaubt die Zustandsgrössen dieses Ausbruchs zu ermitteln. So kann dieser Ausbruch als Musterbeispiel den folgenden Betrachtungen dienen.

DIE LAVAFÖRDERUNG

Verhältnismässig einfach liegt das Problem der Lavaförderung. Die Lava tritt entweder aus dem zylindrischen Förderschlot oder aus Spalten zu Tage.

Der Santorinausbruch ist durch eine kraterlose Staukuppe mit umfangreichem Stromerguss aus dem unter der Staukuppe befindlichen Schlot gekennzeichnet.

Auf der Gipfelkalotte der rund 92 m. hohen Staukuppe spiegelte sich der Querschnitt des Schlotes als lebhaft glühender Kreis mit einem Durchmesser von 40 m. wieder. Damit sind die Schlotdimensionen bekannt. Die Tiefe des Santorinherdes ist unbekannt. Die zähflüssige Staukuppe wurde etwa im Laufe eines Tages aufgestaut. Das Volumen der ersten Tagesförderung berechnete Dobe zu $V = 1{,}198{,}750$ cbm. Bevor sich der Herd entleeren konnte, musste zuerst die Schlotfüllung ausgestossen werden. Nach ihrer Extrusion trat ein kurzer Stillstand in der Entwicklung des Ausbruchs ein. Setzt man diese erste Tagesförderung gleich der Schlotfüllung $V = r^2\pi x$, so würde $x = 954$ m. werden. Das ist ein erster Anhaltepunkt für die Tiefe des Santorinherdes.

Es mag hier vorweggenommen werden, dass die Herdtiefe sich noch auf einem anderen Wege mit Hilfe rein thermodynamischer Daten zu 912 m. berechnen lässt.

Temperaturmessungen an der Schlotmündung sind von Hondros an der heissesten Stelle der Gipfelkalotte der Dafnistaukuppe ausgeführt worden, sie ergaben Temperaturen von 680°, 700°, meist 750°–80°, an Tagen besonders lebhafter Tätigkeit sogar 840° bis 900°.

[1] *Santorin*, Bände I–III (Berlin: D. Reimer, 1936).

Die Wärmeverluste der Lava beruhen auf isothermer Abkühlung, d.h. die Lava kühlt sich durch Wärmeleitung und Ausstrahlung ab. Andererseits heizen die heissen Gase und gleichen die Wärmeverluste z.T. wieder aus. Solange die Lava sich in dem angewärmten Schlot befindet, spielt die isotherme Abkühlung keine sehr grosse Rolle.

Das Problem des Lavaausflusses aus einem zylindrischen Schlot von bekannten Dimensionen entspricht dem Ausfluss einer Flüssigkeit aus einer Röhre, dessen Mechanik lange bekannt ist. Es bedarf nur der Uebertragung auf die besonderen vulkanologischen Fragen.

Es sei v die Durchflussgeschwindigkeit, das in der Zeiteinheit, der Sekunde, aus dem Schlot ausfliessende Lavavolumen in cbcm., r der Schlotradius, l seine Länge, $p_1 - p_2$ das Druckgefälle, der Druck am Anfang und am Ende der Röhre, also im Herd und an der Mündung. Ferner sei η der Reibungsfaktor, das Masz der Viskosität der Lava. Statt der inneren Reibung kann man ihren reziproken Wert, die Fluidität $\varphi = 1/\eta$ benutzen. Alle Grössen sind in C.G. Einheiten auszudrücken.

Die Ausflussgeschwindigkeit als Funktion der inneren Reibung der Flüssigkeit gibt die Poiseuille'sche Formel

$$v = \frac{1}{\eta} \cdot \frac{\pi}{8} r^4 \cdot \frac{p_1 - p_2}{l} . \qquad (1)$$

Das Druckgefälle $p_1 - p_2$ wäre, wenn keine treibenden Gase vorhanden wären, durch das Gewicht des Herddaches oder der Lavasäule im Schlot bestimmt. Mit einer mittleren Dichte der schmelzflüssigen Lava von 2.5 würde 1 At[2] = dem Gewicht einer Gesteinssäule von 1 cm.[2] Querschnitt und 4 m. Länge gleich sein oder 1 m. Gestein entspricht dem Druck von $\frac{1}{4}$ At in C. G. Einheiten 10^2 cm. $= 0.25 \cdot 10^3$ g/cm[2]. Die Gase treiben aber die Lava. Der Herddruck p_1 und der Mündungsdruck p_2 stehen, wie weiter unten noch gezeigt wird, in einem bestimmten Verhältnis, dem kritischen Druckverhältnis zueinander, wenn die Gase mit Schallgeschwindigkeit ausströmen.

[2] Der Einfachheit halber wird hier und im Folgenden 1 At = 1 kg/cm[2] gesetzt, obgleich der exakte Wert 1 At = 1.03328 kg/cm[2] ist. Vulkanologische Grössen sind nie so genau zu bestimmen, dass die Berücksichtigung feinerer Unterschiede einen praktischen Sinn hätte.

Bei 900° ist das kritische Druckverhältnis $p_2 = 0.555\ p_1$. Eine Lavasäule von l m drückt mit $\frac{1}{4}l$ At, dieser Druck ist gleich dem Herddruck im Augenblick des Durchbruchs, $p_1 = \frac{1}{4}\,l$ oder $l = 4p_1$.

$$\frac{p_1 - p_2}{l} = \frac{p_1(1 - 0.555) \cdot 10^3}{4p_1 \cdot 10^2}\ \text{C. G. Einheiten} = 1.11\ \text{C. G. Einheiten.}$$

Die Diskussion der Poiseuille'schen Formel ergibt: Erstens v wird $= 0$, wenn $p_1 - p_2 = 0$ wird, das heisst: Lava fliesst nicht aus, wenn kein Druckgefälle da ist. Zweitens wird $v = 0$, wenn der Koeffizient der inneren Reibung η sehr gross wird, in diesem Falle büsst die Schmelze ihre Beweglichkeit ein und Lava kann nicht ausfliessen. Von technischen Silikatgläsern weiss man, dass der Grad absoluter Starrheit bei 500° mit einem η-Wert von 10^{13} in C. G. Einheiten erreicht ist.

Mit der Poiseuille'schen Formel erhält man die Möglichkeit, die Viskosität einer Lava zahlenmässig zu erfassen. Der Koeffizient der inneren Reibung η ist umgekehrt proportional der Ausflussgeschwindigkeit v:

$$\eta_t = \frac{A}{v}\,,\quad A = \frac{\pi}{8} \cdot r^4 \cdot \frac{p_1 - p_2}{l}\,. \tag{2}$$

In der Konstanten A stecken ausser dem Druckgefälle nur Schlotdimensionen; die Ausflussgeschwindigkeit ist durch Messung zu bestimmen.

Für den Santorinausbruch ergibt die Rechnung: $r = 2.10^3$cm., $(\pi/8)r^4 = 6.2832 \cdot 10^{12}$, $(p_1 - p_2)/l = 1.11$, $A = 6.97435 \cdot 10^{12}$ C. G. Einheiten. Die erste Tagesförderung, die zugleich die grösste des ganzen Ausbruchs war, ist von Dobe zu $V = 1.19877 \cdot 10^{12}$ cm.³ ermittelt worden, das ergibt, mit 1 Tag $= 8.64 \cdot 10^4$ Sekunden, eine Ausflussgeschwindigkeit $v = (1.19875 \cdot 10^{12}/8.64 \cdot 10^4) = 1.38744 \cdot 10^7$ cm³. Man erhält: $\eta_t = A/v = (6.97435 \cdot 10^{12}/1.38744 \cdot 10^7) = 5.02677 \cdot 10^5$ und $\log \eta_t = 5.70128$, ferner $\log\log \eta_t = 0.75597$.

Ordnet man jetzt die grösste Tagesförderung der höchsten gemessenen Temperatur von 900° zu, so besitzt das Santorinmagma bei 900° die Viskosität $\eta_{900°} = 5.0268 \cdot 10^5$ C. G. S. Einheiten oder $\log \eta_{900°} = 5.70128$.

Der Reibungsfaktor η ist ausserordentlich stark temperaturabhängig. An technischen Silikatgläsern ist nach verschiedenen exak-

ten Methoden die Viskosität bei verschiedenen Temperaturen gemessen worden; es ergab sich, dass die Temperaturfunktion gut durch die Gleichung wiedergegeben wurde:

$$\text{loglog}\,\eta = -M \cdot t + P\,. \tag{3}$$

Der doppelte Logarithmus des Reibungskoeffizienten η nimmt proportional mit der Temperatur ab. Die Konstanten M und P können mit $\eta_{500°} = 10^{13}$ und $\eta_{900°} = 5.0268 \cdot 10^{5}$ bestimmt werden. Aus $\text{loglog}\,10^{13} = -M \cdot 500 + P = 1.11394$ und $\text{loglog}\,\eta_{900°} = -M \cdot 900 + P = 0.75597$ folgt: $M = 8.9493 \cdot 10^{-4}$ und $P = 1.56141$. Die Viskositätskurve des Santorinmagmas ist durch die Gleichung bestimmt:

$$\text{loglog}\,\eta = -\,8.9493 \cdot 10^{-4}\,t + 1.56141\,. \tag{4}$$

Figur 1 zeigt die so gewonnene Viskositätskurve des Santorinmagmas, indem auf der Ordinate der log η, auf der Abszisse die Temperaturen in C.° abgetragen wurden.

Diese auf das Santorinmagma eingeeichte Kurve besitzt als Mittelwertskurve für die andesitischen Magmen allgemeine Gültigkeit. Dabei ist noch zu beachten, dass die Viskosität nicht allein von der Temperatur abhängt, sondern dass der Gasgehalt des Magmas einen nicht unbedeutenden Einfluss hat, indem er die Viskosität herabsetzt, die η-Werte werden mit steigendem Gasgehalt kleiner; dieser Einfluss ist ungleich grösser, als die Unterschiede im SiO_2 und Al_2O_3 Gehalt der Magmen.

Washburn und Mitarbeiter[3,4,5] maszen an trocknen Silikatgläsern der Zusammensetzung 70.2 per cent SiO_2, 13.1 per cent Na_2O, 16.7 per cent CaO: log $\eta_{900°} = 6.00$ und log $\eta_{1100°} = 4.45$. Diese Gläser sind nur wenig viskoser als das Santorinmagma.

Die Erweichungsgrenze, das ist die Grenze starr/plastisch und formenbeständig liegt bei log $\eta = 8.6$ und 700°, die Flussgrenze,

[3] W. Eitel, *Physikalische Chemie der Silikate* (Leipzig: E. Voss, 1929), SS. 64–76.

[4] E. W. Washburn, G. R. Shelton und E. E. Libman, "The Viscosities and Surface Tensions of the Soda Lime-Silica Glasses at High Temperature," *Univ. of Ill. Eng. Exper. Stat. Bull. 140*, Vol. XXI, No. 33 (1924).

[5] H. Le Chatelier, "Sur le viscosité du verre," *CR*, Vol. CLXXIX (1924), pp. 517–21.

die Grenze plastisch/ flüssig, etwa bei log $\eta = 7.0$ und rund 800°. Die Erweichungstemperatur wurde an wieder erhitztem Andesit,

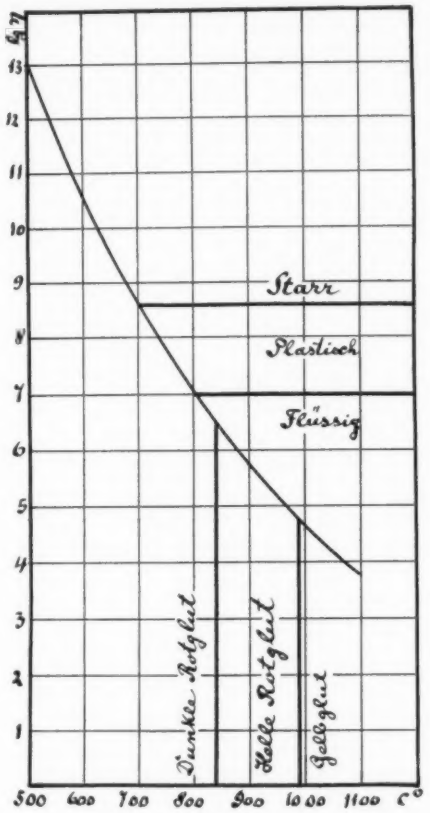


FIG. 1.—Viskositätskurve andesitischer Magmen

der seinen Gasgehalt bei der Erstarrung zum grössten Teil bereits abgegeben hat, bestimmt zu: 800° (Kotô), 904°–38° (Lacroix),[6] 1050°–98° (Brun), die Flussgrenze—die Temperatur der Knotenbildung von Glasstäben—zu: 1050° (Lacroix), 1050°–98° (Brun).

[6] A. Lacroix, *La Montagne Pelée après ses éruptions* (Paris: Masson et Cie, 1908), S. 54.

Die sichtbare Strahlungsgrenze liegt bei 600°, von 840°–990° reicht die helle Rotglut, darüber hinaus Gelbglut und schliesslich Weissglut. Diese Grenzen sind brauchbare Anhaltepunkte für Temperaturschätzungen besonders in der Nacht. Mit Hilfe der Viskositätskurve lassen sich nun die zu den log η-Werten gehörigen Temperaturen ablesen, wenn die jeweiligen Tagesförderungen an Lava gegeben sind, die mit ihren Ausflussgeschwindigkeiten den betreffen-

TABELLE 1

SANTORINAUSBRUCH 1925–26

Datum	Tagesförderung in Cbm.	log η	t Berechn.	t Gemess.
13. 8. 25	1 198 750	5.70128	900°	
18. 8. 25	1 053 500	5.75738	895	
31. 8. 25	202 900	6.47273	840	
11. 9. 25	241 100	6.39781	846	
17. 9. 25	904 400	5.82365	890	
10.10. 25	345 751	6.24125	857	
18.10. 25				750°–780°
19.10. 25				750 –780
20.10. 25	699 640	5.93514	881	750
21.10. 25				840 –900
31.10. 25	911 636	5.82019	890	
10.11. 25	613 144	5.99245	876	
20.11. 25	894 820	5.82827	890	
14.12. 25	277 400	6.33686	850	
28.12. 25	919 000	5.81669	890	
1. 4. 26	287 000	5.33597	850	
Nautilus 3–7.3.28	10 000	7.78001	756	

den Reibungskoeffizienten ergeben. In Tabelle 1 ist diese Rechnung für den Santorinausbruch durchgeführt. Es zeigt sich, dass die mit η errechneten Temperaturen durchaus innerhalb der Variationsbreite der mit dem Pyrometer gemessenen Temperaturen liegen. Das gasreiche Santorinmagma ist, wie Tabelle 1 zeigt, noch bis zu 840° geflossen. Der Nautiluspfropfen befand sich mit 756° in einem plastischen und formkonstanten Zustand. Die Entstehungstemperatur der Staukuppe lag also zwischen 756° und 840°. Die höchsten während eines Paroxysmus gemessenen Temperaturen von 900° bis 950° haben die Staukuppe nicht mehr zum Auseinanderfliessen gebracht. 780° bis 800° dürfte der Entstehungstemperatur der Dafnistaukuppe am nächsten kommen.

Die Viskosität der Lava ist eine wichtige Zustandsgrösse, sie ist in erster Linie temperaturbedingt, sie beherrscht die vulkanische Morphologie. Das Verhältnis von Höhe zum Basisdurchmesser $H:D$ der Staukuppen ist, wie R. von Leyden[7] gezeigt hat, eine Funktion der Viskosität. Sie lässt sich auf Grund der obigen Untersuchungen durch die Kurve der Figur 2 darstellen. Dieselbe verläuft asymptotisch zu den Koordinatenaxen und biegt im plastischen

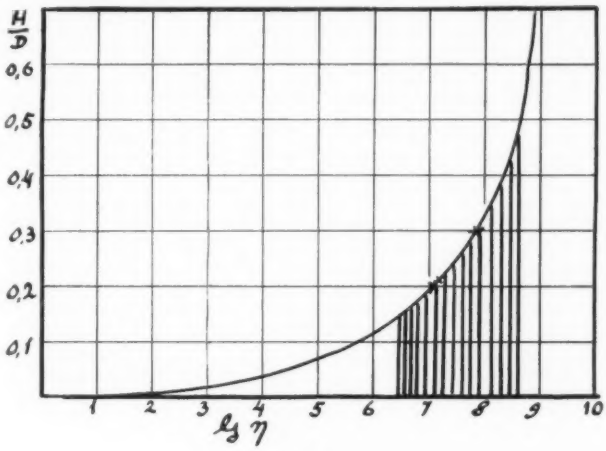


FIG. 2

Gebiet (schraffiert) um. Zwischen log $\eta = 6.5$ und log $\eta = 8.6$ (Starrgrenze) bewegt sich H/D von 0.1 bis 0.5. Die Voraussetzung für die richtige Ermittelung von H/D ist, dass die Formung der Staukuppe frei und nicht durch die Trichterwände des Kraters behindert erfolgt. Mit Hilfe der Viskositätskurve lässt sich aus H/D die Bildungstemperatur wenigstens angenähert entnehmen. Als Fixpunkte der Kurve dienten: Dafnikuppe $H/D = 22:110 = 0.2$ mit log $\eta = 7$, Nautilus: $H/D = 15.6:74 = 0.21$ und log $\eta = 7.6$, Lassen Peak: $H/D = 300:1000 = 0.3$ und log $\eta = 7.8$.

DIE GASFÖRDERUNG

Der Gasstrom unterscheidet sich von dem Flüssigkeitsstrom grundlegend dadurch, dass er nicht volumenbeständig bleibt. Das

[7] "Staukuppen und verwandte Bildungen," *Z. f. Vulk.*, Band XVI (1936), SS. 225–47.

Ausströmen von Gasen und Dämpfen aus einer zylindrischen Röhre ist im Grunde genommen das gleiche Problem, das im vorigen Abschnitt behandelt wurde, nur durch die adiabatische Ausdehnung und Abkühlung verwickelter. Wenn Gase in der Richtung eines Druckgefälles strömen, so dehnen sie sich aus und kühlen sich dabei ab. Diese Ausdehnung und Abkühlung heisst adiabatisch, weil die Energieänderungen die Grenzen des Systems nicht überschreiten, da die bei der Volumenausdehnung geleistete Arbeit als Wärmeäquivalent dem Wärmeinhalt entzogen wird und nicht nach Aussen abgegeben wird.

Um den Zustand eines Gases zu kennzeichnen, reicht die Temperatur allein nicht mehr aus. Es muss entweder Temperatur und Druck, Spannung der Gase, oder Temperatur und Volumen, spezifisches Volumen—Volumen der Masseneinheit, oder Druck und Volumen bekannt sein, dann ist die dritte Zustandsgrösse aus den Adiabatengleichungen zu entnehmen.

Es bezeichne T die Temperatur in absoluter Zählung (Nullpunkt $-273°$), p den Druck in Atmosphären, V das Volumen, so lauten die Adiabatengleichungen:

$$T_1 \cdot V_1^{\kappa-1} = T_2 \cdot V_2^{\kappa-1} \tag{5}$$

$$p_1 \cdot V_1^{\kappa} = p_2 \cdot V_2^{\kappa} \tag{6}$$

$$T_1^{\kappa} \cdot p_1^{1-\kappa} = T_2^{\kappa} \cdot p_2^{1-\kappa} . \tag{7}$$

Die dritte Gleichung ist die wichtigste für vulkanologische Fragen, sie lässt sich in bequemerer logarithmischer Form so schreiben:

$$\kappa(\log T_1 - \log T_2) = (\kappa - 1)(\log p_1 - \log p_2) \tag{8}$$

oder:

$$\log p_1 = \log p_2 + \frac{\kappa}{\kappa - 1} \cdot (\log T_1 - \log T_2) \tag{8a}$$

$$\log T_1 = \log T_2 + \frac{\kappa - 1}{\kappa} (\log p_1 - \log p_2) . \tag{8b}$$

Von den drei Grössen T, p, V der Gleichungen ist am Vulkan nur die Temperatur unmittelbar messbar, der Druck ist auf Umwegen durch die leicht messbare Steighöhe der Eruptionswolke berechenbar.

Der adiabatische Exponent.—Der adiabatische Exponent ist das Verhältnis der Molekularwärmen bei konstantem Druck und bei konstantem Volumen, $\kappa = C_p : C_V$. Die beiden Molekularwärmen sind durch die Gaskonstante mit einander verknüpft: $C_p - C_V = R = 1.988$ cal. Nun gelten diese Beziehungen streng nur für den Grenzfall des idealen Gases. Die hochgespannten, heissen vulkanischen Gase und Dämpfe entsprechen gewiss nicht diesem Zustand, sie sind Gasgemische sehr verschiedener Zusammensetzung, die nicht zu erfassen ist, hochgespannter Wasserdampf bildet jedoch den Hauptanteil. Korrekturen, die durch die Abweichungen von den idealen Gasgesetzen notwendig wären, lassen sich nicht anbringen. Für den Wasserdampf sind die Molekularwärmen C_V und auch die κ-Werte bis zu den höchsten Temperaturen gemessen, sodass diese Konstanten als ausreichend gesichert gelten können. Das Diagramm Figur 3 gibt die Temperaturabhängigkeit von κ und C_p, $C_p = C_V + R$ für den Wasserdampf wieder, zu Grunde gelegt sind die Werte:

t^0	0°	500°	1200°
C_v	5.93	7.04	8.60
C_p	7.92	9.03	10.59
κ	1.33	1.29	1.23

Der adiabatische Exponent[8] ändert sich mit dem Stoff, der Gasart und mit der Temperatur. Andere vulkanische Gase besitzen bei 0° folgende adiabatische Exponenten: N_2, O_2, HCl, CO = 1.40; CO_2, SO_2 = 1.29; NH_3 = 1.29; Wasserdampf mit 1.33 liegt nahezu in der Mitte.

Die Spannung der Gase und Dämpfe.—Die wichtigste Aufgabe ist es, den Druck p in Atmosphären zu ermitteln, unter dem der Wasserdampf bei der Eruption an der Schlotmündung steht. Der Wasserdampf steigt als Strom aus dem Schlot, normaler Weise senkrecht in die Höhe, dabei dehnt er sich aus und kühlt sich ab. Die adiabatische Ausdehnung findet im Entspannungszustand ihr Ende. Dieser End-

[8] K. Jellinek, *Lehrbuch der physikalischen Chemie*, Band I (Stuttgart bei Enke, 1914), S. 131.

zustand ist erreicht, sobald der sich entspannende Wasserdampf der Eruptionswolke sich mit dem Luftdruck der Umgebung in ein Gleichgewicht gesetzt hat. Die Höhe, in der die Angleichung des Drucks des entspannten Wasserdampfs p_0 an den Luftdruck erfolgt ist, ist die Steighöhe der Eruptionswolke h. Die adiabatische Abkühlung erreicht ein Ende im Kondensationspunkt des Wasserdampfs in dieser Höhe, denn eine weitere Abkühlung der flüssigen Wasserphase ist von da ab isotherm und nicht mehr adiabatisch.

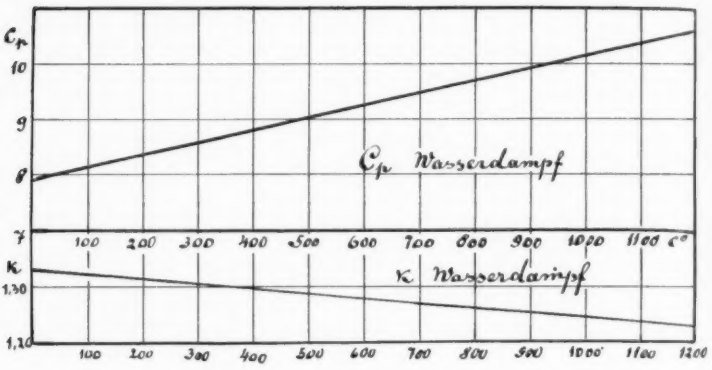


FIG. 3

Die Kondensationstemperaturen des Wasserdampfs in ihrer Abhängigkeit vom Druck sind bekannte physikalische Grössen.

Die Zustandsgrössen des Endzustandes, Entspannungszustandes p_O, t_O, T_O sind mit Hilfe der Steighöhe der Eruptionswolke durch den Druck und die Kondensationstemperatur des Wasserdampfs in dieser Höhe zu bestimmen. Ist dann noch die Temperatur des Wasserdampfs an der Schlotmündung bekannt, so folgt seine Spannung ohne Weiteres aus der dritten Adiabatengleichung (7).

Im Folgenden sollen die Zustandsgrössen im Herd, also am Anfang des Schlotes, mit dem Index 1, die der Schlotmündung, am Ende des Schlotes mit dem Index 2 und die des Entspannungszustandes mit O gekennzeichnet werden.

Die Steighöhe der Eruptionswolken.—Mit zunehmender Höhe über dem Meere nimmt der hydrostatische Druck der Luft in geometri-

schen Progressionen ab. Die bekannte barometrische Höhenformel gibt die Höhe als Funktion des Luftdrucks in folgender Weise an:

$$h = 18\,400\,(1 + 0.004 \cdot t) \cdot (\log b_0 - \log b) \qquad (9)$$

h ist die Steighöhe der Eruptionswolke, t die mittlere Temperatur der Luftsäule, b der Barometerstand in der Höhe h, b_0 am Meeresspiegel.

Diese Grössen hängen noch von der jeweiligen Wetterlage ab. Es hat aber für das vorliegende Problem wenig Zweck, solche Korrekturen zu versuchen anzubringen, da die nötigen Unterlagen bei einem Ausbruch doch fehlen. Die Rechnung lässt sich nur für einen Standardfall mit Mittelwerten durchführen. Mit $b_0 = 760$ mm. Quecksilbersäule und einer mittleren Temperatur $t = 15°$ erhält man:

$$h = 19504\,(\log 760 - \log b) \qquad (10)$$

$$\log b = 2.88081 - \frac{h}{19504} \qquad (10a)$$

b mm. Quecksilber entspricht in Atmosphären umgerechnet, 1 At = 760 mm., dem Entspannungsdruck p_0, die dazu gehörige Kondensationstemperaturen sind aus den Tabellen der Spannkraft des Wasserdampfs zu entnehmen. In Tabelle 2 mögen als Beispiel die Entspannungsgrössen für einige Steighöhen zusammengestellt werden.

TABELLE 2

$h =$	3160 m.	3000 m.	2500 m.	2000 m.	1500 m.	1000 m.	500 m.	150 m.
$b =$	523 mm.	533 mm.	566 mm.	600 mm.	637 mm.	675 mm.	716 mm.	747 mm.
$p_0 =$	0.688	0.700	0.745	0.790	0.839	0.888	0.942	0.982
$t_0 =$	89.9°	90.5°	92°	93.6°	95.2°	96.7°	98.3°	99.5°

Berechnung der Mündungsspannung am Santorinschlot.—Für den Santorinausbruch im 1. Paroxysmusstadium ist am 19.8.25 eine Steighöhe von $h = 3160$ m. gemessen worden. Die maximale Mündungstemperatur ergab: $t_2 = 900°$, $T_2 = 1173°$, die Entspannungsgrössen für die Höhe 3160 m. sind: $p_0 = 523$ mm. $Hg = 0.688$. At, $t_0 = 89.9°$, $T_0 = 362.9°$, die adiabatische Abkühlung geht von 900°

bis 90°, im Mittel über 500°, für das der adiabatische Exponent $\kappa_{500°} = 1.29$ zu benutzen ist. Die dritte Adiabatengleichung (Formel 8*a*) nimmt die Gestalt an: $\log p_2 = \log p_0 + \kappa/(\kappa - 1)(\log T_2 - \log T_0)$, $\kappa/(\kappa - 1) = 4.448$. Die obigen Werte eingesetzt, liefern für den Santorinausbruch zur Mündungstemperatur $t_2 = 900°$ die Mündungsspannung $p_2 = 127$ At.

In Tabelle 3 sind für eine Anzahl Steighöhen und Mündungstemperaturen die Mündungsspannungen berechnet. Diese Zahlenreihen lehren, dass die Steighöhe umso kleiner ist, je höher bei gleicher Mündungstemperatur die Spannung der Gase ist. Bei gleicher Mündungsspannung nimmt die Steighöhe mit der Mündungstemperatur zu. Die Beziehung zwischen Steighöhe, Mündungsdruck, und Mündungstemperatur mag das Diagramm Figur 4 veranschaulichen.

TABELLE 3

Steighöhe *h*	900° (At)	850° (At)	800° (At)	700° (At)	t_0	p_0 (At)	Datum
3160 m.....	127	105	85	55	89°9	0.688	19. 8.25
2000.....	140	116	94	61	93.6	.790	21. 4.26 Schlussexplosion
1500.....	145	120	98	63	95.2	.839	23. 8.25
1000.....	151	124	102	65	96.7	0.888	25.10.25

Die Erklärung ist einfach. Je höher die Mündungsspannung ist, desto schneller geht die Entspannung vor sich, die adiabatische Abkühlung ist stärker, der Kondensationspunkt des Wasserdampfs wird schneller erreicht, die Steighöhe ist kleiner. Hohe Mündungstemperaturen brauchen längere Zeit zur Abkühlung und die Wolken steigen entsprechend höher hinauf.

Eisenchloriddämpfe.—Bei dem Santorinausbruch konnte man in den Pausen zwischen zwei paroxysmalen Eruptionsstössen braune Eisenchloridschleier beobachten, die 150 m. hoch aufstiegen. Für das Eisenchlorid $FeCl_3$ ist bekannt, dass sein Kondensationspunkt bei 307° und einem Druck von ungefähr 1 At liegt. In 150 m. Höhe herrscht ein Luftdruck von 747 mm. $Hg = 0.982$ At, $t_0 = 307°$. Die Molekularwärmen des $FeCl_3$ sind nicht bekannt. Benutzt man die

Werte des analog gebauten Moleküls NH_3: $C_V = 8.52$, $C_p = 10.56$ und $\kappa_{500°} = 1.23$, so erhält man bei einer Steighöhe $h = 150$ m. für

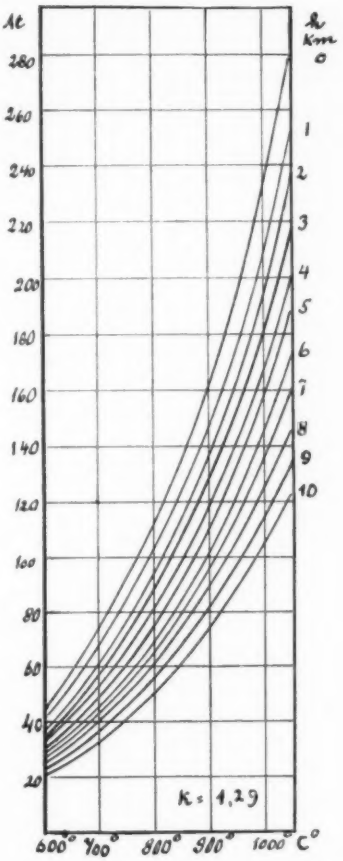


FIG. 4.—Steighöhe, Mündungs-Druck und Temperatur

verschiedene Mündungstemperaturen die folgenden Mündungsspannungen:

$t_2 =$	900°	850°	800°	700°
$p_2 =$	42 At	34 At	26 At	16 At

Die Energieverausgabung während einer Paroxysmuswelle zog einen starken Spannungsabfall an der Schlotmündung nach sich, während die Temperatur noch hoch blieb. Sank die Spannung etwa auf ein Drittel ihres Anfangswertes, so konnten sich die Eisenchloriddämpfe in den Pausen entwickeln. Als Grenzwert für die Steighöhe o m., $p_0 = 1$ At findet man $t_2 = 308°$, das heisst: Fumarolen, welche $FeCl_3$ Dämpfe aushauchen, müssen heisser als 308° sein.

Ausflussgeschwindigkeit der Gase.—Die Gesetze der Gasbewegung[9] durch eine Röhre lassen sich ohne Weiteres auf den Vulkan anwenden.

Die Ausflussgeschwindigkeit im Kessel, bezw. Vulkanherd, w ist anfänglich = o. Der Dampf strömt durch die Röhre, Vulkanschlot, mit wachsender Geschwindigkeit. An der Stelle, wo der Stromfadenquerschnitt am kleinsten ist, wird die Stromgeschwindigkeit gleich der Schallgeschwindigkeit $w = a$. Nach Ueberwindung der Profilenge überwiegt die adiabatische Ausdehnung und die Stromgeschwindigkeit wird grösser als die Schallgeschwindigkeit. Diese trennt das Gebiet der Unterschallgeschwindigkeit von dem der Ueberschallgeschwindigkeit. Die Schallgeschwindigkeit heisst deshalb auch die kritische Stromgeschwindigkeit.

Beim Vulkan fällt das Stromfadenquerschnittsminimum mit der Schlotmündung zusammen. Das beweisen die Detonationen beim Hervorbrechen der Gaswellen aus der Schlotmündung. In den "flashing arcs" werden die Schallwellen sogar optisch sichtbar und lassen sich photographieren. Wenn überdies, wie beim Santorinvulkan, über der Schlotmündung eine Staukuppe als riesiger für Gase durchlässiger Ventildeckel ruht, so liegt hier ohne Zweifel die grösste Verengung des Stromprofils.

Strömungsgeschwindigkeit und Schallgeschwindigkeit werden gleich bei dem kritischen Druckverhältnis:

$$\frac{p'}{p_1} = \left(\frac{2}{\kappa + 1}\right)^{\kappa/(\kappa-1)}. \qquad (11)$$

κ ist wieder der adiabatische Exponent, p_1 der Kessell bezw. Herddruck am Beginn des Förderschlotes. Für den Fall, dass die Dämpfe

[9] A. Busemann, "Flüssigkeits- und Gasbewegung," *Handwörterbuch der Naturwissenschaften*, Band IV (2. Auflage; Jena: G. Fischer, 1934), SS. 268–69.

mit kritischer Geschwindigkeit, d.h. Schallgeschwindigkeit, ausströmen, wie das für Vulkanausbrüche wohl allgemein angenommen werden darf, wird $p' = p_2$, dem Mündungsdruck und

$$\frac{p_2}{p_1} = \left(\frac{2}{\kappa + 1}\right)^{\kappa/(\kappa-1)} . \tag{11a}$$

Das kritische Druckverhältnis in die dritte Adiabatengleichung eingesetzt, liefert das kritische Temperaturverhältnis

$$T_1 : T_2 = \tfrac{1}{2}(\kappa + 1) . \tag{11b}$$

Mit Hilfe der Tabelle 4 findet man für das mittlere Temperaturgebiet von 1000° mit $\kappa_{1000°} = 1.24$ zum Mündungsdruck $p_2 = 127$

TABELLE 4

κ	$p_1 : p_2$	$T_1 : T_2$
1.24	1.796	1.120
1.25	1.802	1.125
1.26	1.808	1.130
1.27	1.814	1.135
1.28	1.820	1.140
1.29	1.826	1.145

At den Herddruck $p_1 = 228$ At und zur Mündungstemperatur $t_2 = 900°$, $T_2 = 1173°$ die Herdtemperatur $T_1 = 1314°$ oder $t_1 = 1041°$.

Nimmt man ferner an, dass die Herdspannung von 228 At bei dem ersten wegbahnenden Paroxysmus grade so gross war, um den Durchbruch zu erzwingen und das Gegengewicht des Herddaches oder der Schlotfüllung zu überwinden, so ergibt sich die Herdtiefe, x—1 At = 4 m. Gesteinssäule gesetzt—$x = 4 \times 228$ m. = 912 m.

Diese thermodynamisch errechnete Herdtiefe stimmt der Grössenordnung gut mit der auf Grund der erster Lavaförderung geschätzten Herdtiefe von 954 m. überein.

Die Theorie der Gasbewegung gibt ferner für eine durch das Druckgefälle p_1 nach p_2 erzeugte Stromgeschwindigkeit die Formel:

$$w_{1,2} = \sqrt{\frac{2\kappa}{\kappa - 1} \cdot p_1 V_1 \cdot \left[1 - \left(\frac{p_2}{p_1}\right)^{(\kappa-1)/\kappa}\right]} \tag{12}$$

die sich im Fall der Schallgeschwindigkeit vereinfacht zu:

$$w = a = \sqrt{\kappa \cdot \frac{p}{\rho}}, \text{ wo } \rho = \text{Dichte des Gases.} \qquad (13)$$

Die Schallgeschwindigkeit in Wasserdampf.—Formel 13 ist unter dem Namen "Laplace'scheFormel" bekannt und wird benutzt, um die Schallgeschwindigkeit in Gasen zu bestimmen.

Der Druck des Gases sei in h cm. Quecksilbersäule gegeben, dann ist mit der Dichte das Quecksilbers 13.333, $p = 13.333 \cdot h$ g/cm². Mit dem kubischen Ausdehnungskoeffizienten der Gase $\alpha = 3.67 \cdot 10^{-3}$ wird $V = V_0 \cdot (1 + \alpha t)$ und die Dichte $\rho = 1/V$ bei einem Gasdruck von h cm. Hg und $t°$ $\rho = \rho_0 \cdot h/76 : (1 + \alpha t)$, $\kappa_{0°} = 1.33$. Diese Werte in die Laplace'sche Formel eingesetzt, ergeben:

$$a^2 = 1.33 \cdot \frac{13.333 \cdot h(1 + \alpha t)}{\frac{h}{76} \cdot \rho_0} = \frac{101\ 3.308 \cdot \kappa(1 + \alpha t)}{\rho_0} \text{ (cm/sek)}^2.$$

Trockne Luft besitzt bei 0° die Dichte $\rho_0 = 1.2936 \cdot 10^{-3}$, die Dichte des Wasserdampfs ist etwa $\frac{5}{8}$ des Luftwertes, also $\rho_0 = 0.8085 \cdot 10^{-3}$. Mit diesen Werten erhält man:

$$a_t^2 = \frac{101\ 3.308 \cdot 1.33(1 + 3.67 \cdot 10^{-3} \cdot t)}{0.8085 \cdot 10^{-3}} \text{ (cm/sek)}^2 \text{ oder}$$

$$a_t = 408 \cdot \sqrt{1 + 3.67 \cdot 10^{-3} \cdot t} \text{ m/sek} \qquad (14)$$

$t =$	500°	700°	800°	900°	1000°	1100°	
$a =$	687	770	810	846	882	916	m/sek.

Die Temperaturabhängigkeit der Schallgeschwindigkeit in Wasserdampf stellt Figur 5 dar.

Der Wärmeinhalt.—Der Wärmeinhalt i der Masseneinheit liefert das kalorische Masz des Energieinhalts. Diese Grösse ist, wie keine andere, geeignet, die Intensität eines Vulkanausbruchs exakt zu bestimmen. Der Wärmeinhalt der Masseneinheit ist mit dem Druck —daher die Bezeichnung "Druckfunktion"—durch die Beziehung verknüpft

$$i = \frac{\kappa}{\kappa - 1} \cdot p \cdot V = \frac{\kappa}{\kappa - 1} \cdot p_1 \cdot V_1 \cdot \frac{p^{(\kappa-1)/\kappa}}{p_1} \qquad (15)$$

mit der Stromgeschwindigkeit für den Druckabfall p_1 auf p_2:

$$w_{1,2} = \sqrt{2(i_1 - i_2)} \,. \tag{16}$$

Für den Sonderfall der Schallgeschwindigkeit wird

$$a = \sqrt{(\kappa - 1)i} \,. \tag{17}$$

Für den Santorinausbruch $h = 3160$ m., $t_2 = 900°$, $p_2 = 127$ At, $t_1 = 1041°$, $p_1 = 228$ At wird die durch den Druckabfall p_1 nach p_2

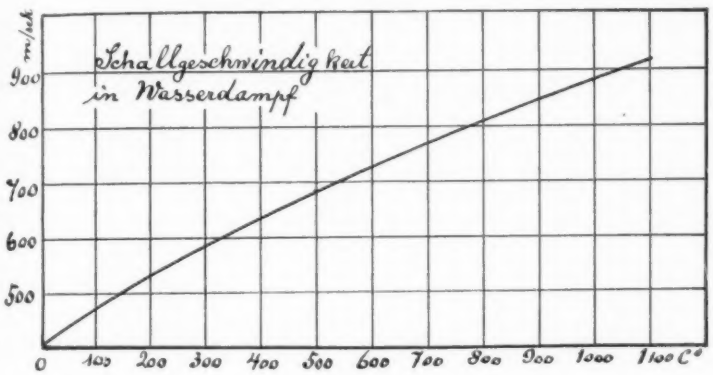


FIG. 5

bewirkte Stromgeschwindigkeit zur Schallgeschwindigkeit, die mit $\kappa = 1.25$, $a = 84600$ cm/sek ist.

Somit ist: (Formel 16 und 17) $2(i_1 - i_2) = (\kappa_1 - 1)i_2 = 0.25\ i_2$, $i_1 = 9/8 \cdot i_2$ und $a^2 = (\kappa - 1) \cdot i_2 = 84600^2 = 0.25 \cdot i_2$. Daraus ergibt sich $i_2 = 2.86286 \cdot 10^{10}$ und $i_1 = 3.22072 \cdot 10^{10}$ Grammkalorien.

Mit Hilfe der Formel 15 sind nunmehr auch die übrigen Zustandsgrössen leicht zu finden. Diese Tabelle enthält die Zustandsgrössen des Anfangs und Endzustands. Der Ausbruch hat 284 Tage gedauert, $108 \cdot 10^6$ cbm. Lava sind gefördert worden. Die Herdenergie ist von $i_1 = 3.22 \cdot 10^{10}$ cal. pro Masseneinheit im Anfangszustand auf $i_1 = 2.47 \cdot 10^{10}$ cal. des Endzustands um $0.75 \cdot 10^{10}$ cal. zurückgegangen, das macht etwa 23 per cent aus, es ist das Masz für die Erschöpfung.

Die Wiederauffüllung der durch eine Ausbruchsperiode verausgabten Energiemenge ist nur in der Richtung des Wärmegefälles möglich, also aus der Tiefe. Nur Gase kommen als die eigentlichen Träger der Wärme in Frage. Ein Vulkanherd bleibt also nur solange tätig, als sein Wärmevorrat durch Gase aus der Tiefe immer wieder ergänzt wird. Die Ruhepausen zwischen zwei Eruptionsperioden

TABELLE 5

SANTORIN*

	h	t_0	p_0	t_2	p_2	κ	t_1	p_1
Anfang 19.8.25.	3160 m.	89.9°	0.688 At	900°	127 At	1.25	1041	228 At
	i_2	V_2	ρ_2	i_1	V_1	ρ_1		
	2.8629 $\times 10^{10}$ cal.	4.632 $\times 10^4$ cm.^{3}	2.2919 $\times 10^{-5}$	3.2208 $\times 10^{10}$ cal.	2.6521 $\times 10^4$ cm.^{3}	3.7706 $\times 10^{-5}$		
Ende 21.5.26.	h	t_0	p_0	t_2	p_2	t_1	p_1	
	2000 m.	93.6°	0.790 At	700° geschätzt	54 127 At	827°	98 At	
	i_2	V_2	ρ_2	i_1	V_1	ρ_1		
	2.1959 $\times 10^{10}$ cal.	8.3662 $\times 10^4$ cm.^{3}	1.1963 $\times 10^{-5}$	2.4704 $\times 10^{10}$ cal.	5.1863 $\times 10^4$ cm.^{3}	1.9279 $\times 10^{-5}$		

* Schlotradius $r = 20$ m.; Herdtiefe $x = 912$ m.

hängen einmal vom Grade der Erschöpfung des Herdes durch den letzten Ausbruch ab, dann von der Schnelligkeit der Wärmezufuhr aus der Tiefe. Beide Faktoren sind nicht konstant in der Zeit, so darf man auch keine regelmässigen Perioden in der Geschichte eines Vulkans erwarten.

Ist die Energieerschöpfung nach einem grossen Ausbruch sehr gross, so muss auch der Volumenschwund des Vulkanherdes sehr gross sein; es kann dann unter Umständen zum Einbruch des Herddaches kommen, eine Kaldera entsteht.

Es wäre sehr interessant auch die Zustandsgrössen des vorausge-

gangenen Santorinausbruchs aus dem Jahre 1866 zu berechnen, um den Vergleich beiden artgleichen Eruptionen zu vertiefen. Der Mangel exakter Temperaturmessungen lässt leider die Rechnungsgrundlagen nicht ausreichen

Die Ausflussmassen der Gase.—Es bezeichne M die in der Zeiteinheit ausströmende Gasmenge, F der Stromfadenquerschnitt, w die Strömungsgeschwindigkeit, ρ die Dichte des Gases, so ist:

$$M = F \cdot w \cdot \rho \,. \tag{18}$$

Für den ersten Santorinparoxysmus erhält man mit dem Schlotquerschnitt $F = 2000^2 \cdot \pi$ cm.^{2}, $w_{900°} = 84600$ cm/sek und $\rho_{900°} = 2.2919 \cdot 10^{-5}$, $M = 2.43 \cdot 10^7$ g oder $1.063 \cdot 10^{12}$ cm.^{3} in der Sekunde. Der Paroxysmus dauerte 15 Minuten und förderte dabei $9.568 \cdot 10^8$ cbm. Gas von 900° und 127 At Spannung.

VERGLEICH MIT ANDEREN ANDESITISCHEN VULKANAUSBRÜCHEN

Im folgenden sind die Zustandsgrössen des Santorinausbruchs mit einigen anderen bekannten andesitischen Ausbruchstypen zu vergleichen.

SAKURA-JIMA 1914

Der japanische Vulkan Sakura-jima in des Kagoshimabucht hatte vom 12.1.–7.2.1914 einen doppelseitigen Flankenausbruch, der von Kotô[10] beschrieben worden ist. Aus dem Yunohiraschlot entsprang das westliche Lavafeld mit einer Lavaförderung in 12 Tagen, vom 16.–27.1.14. von 0.2881 cbkm; das östliche Lavafeld ging vom Nabeyama aus und lieferte in 6 Tagen, vom 28.1.–2.2.14. 0.8529 cbkm. Staukuppenbildung stellte sich im Gegensatz zu Santorin erst in der abklingenden Phase am Yunohiraschlot ein. Mit einem Hollborn-Kurlbaumpyrometer wurden in den Spalten der Lava Gelbglut mit Temperaturen von 995°–1048° gemessen, in den rot glühenden Partien 857°. Der Ausbruch war für einen Andesitvulkan ungewöhnlich heiss. Die erste Steighöhe der Eruptionswolke wurde von dem Stationsvorsteher der Eisenbahn in Kagoshima zu 18 181 m. gemessen, später während der strombolianischen Phase betrug die Steighöhe nach Messungen von T. Ogura nur noch 3000 bis 4000 m. Mit diesen Daten errechnen sich folgende Zustandsgrössen

[10] Bundjirô Kotô, "The Great Eruption of Sakura-jima in 1914," *Jour. Coll. Sci.*, Vol. XXXVIII, Art. 3 (Tokyo: Imperial University, 1916), p. 237.

(Tabelle 6). Anfänglich war das Magma mit der Steighöhe 18 km. heiss (1048°) und wenig gespannt (74 At). Das Magma der strombolianischen Phase war heiss und höher gespannt (244 At), es kam sicher aus grösserer Tiefe. Kotô nahm zur Erklärung des Eruptionsmechanismus eine bilateral sattelitische Injektion an.

Zuerst trat der niedrig gespannte Sekudärherd in Tätigkeit, dann erst der hochgespannte tiefere Hauptherd. Seine Tiefe veranschlagt Kotô auf wenigstens 1000 m., da der Vulkan gefrittete Granit-

TABELLE 6

SAKURA-JIMA

h	t_0	p_0	t_2	p_2	κ	i_2	t_1	p_1	i_1
18 181 m.*	49°	0.117 At	1048°	74 At	1.24	3.375×10^{10}	1207°	133 At	$3.717 \cdot 10^{10}$

h	t_0	p_0	t_2	p_2	κ	t_1	p_1
3560 m.†	890	0.657 At	1048°	244 At	1.24	1207°	438 At

* Herdtiefe $x = 532$ m. † Herdtiefe $x = 1752$ m.

auswürflinge heraufgebracht hat. In dieser Tiefe durchbricht der Granit die mesozoischen Schiefer des Untergrunds.

MONT PELÉ 1902

Der von Lacroix[11] beschriebene Peléausbruch 1902 auf Martinique bestand in der Extrusion einer Staukuppe, dem Dom, aus dem vom 3.11.02 ab eine feste Felsnadel herausgepresst wurde. Aufsteigende und besonders absteigende Eruptionswolken waren die Begleiterscheinungen. Die Felsnadel war ein Zylinder von 150 m. Durchmesser entsprechend den Dimensionen des Förderrohres.[12] Direkte Temperaturmessungen sind nicht gemacht. Der wegbahnende Paroxysmus erreichte eine Steighöhe seiner vertikalen Eruptionswolke von 10,000 m., Grenze des Passats und Antipassats. Die Temperatur der absteigenden Eruptionswolken, Lacroix's "Glut-

[11] A. Lacroix, *La Montagne Pelée et ses éruptions* (Paris: Masson et Cie, 1904).

[12] *Ibid.*, S. 1321.

wolken," die nur nachts an der Schlotmündung als glühend zu sehen waren, ergibt folgende Rechnung.

Am 6.11.02 erreichte die Felsnadel eine Meereshöhe von 1575 m., oder eine relative Höhe über der Schlotmündung von 565 m., wenn man die Schlotmündung in 1010 m. Meereshöhe ansetzt.

Der Mündungsdruck musste also einer Gesteinssäule von 565 m. Höhe das Gleichgewicht halten. 1 m. Gestein = $\frac{1}{4}$ At gesetzt, liefert den Mündungsdruck $p_2 = \frac{1}{4}$ 565 At = 141 At. Die Steighöhe der vertikalen Eruptionswolken war in diesen Tagen zu 1500 m. eingemessen, sie lieferte die Entspannungsgrössen $t_0 = 95°$, $p_0 = 0.839$ At. Mit p_2, p_0, t_0 ergibt sich aus der 3. Adiabatengleichung die Mündungstemperatur t_2 und damit die Anfangstemperatur der "Glutwolke" zu 893°.

Die Staukuppe, ein glühender Blockhaufen besass nach Lacroix's Schätzung ein Volumen von über 10^8 cbm., sie war im wesentlichen in einem Tage aufgebaut. Mit dieser Tagesförderung und den Schlotdimensionen ergibt die Poiseuille'sche Formel $\log \eta \sim 6.0$ und eine Entstehungstemperatur von 860°–80°. Nach Lacroix war die Staukuppenkruste tridymitreich, ihr Kern quarzreich. Die Entstehungstemperatur der Staukuppe muss deshalb oberhalb des Umwandlungspunktes Tridymit-Quarz bei 840° gelegen haben.

In gleicher Weise berechnet sich auch die Temperatur der festen Felsnadel für einen täglichen Höhenzuwachs von 5 bis 60 m. Die Rechnungsergebnisse sind auf Tabelle 7 zusammengestellt.

LASSEN PEAK 1914–15

Der Ausbruch des Lassen Peak, 3189.9 m., in der Shasta County Nordostkalifornien im Mai, 1914, ist die kälteste andesitische Eruption, die man kennt. Day und Allen[13] haben auf indirektem Wege die Temperatur auf 600° bis 750° einengen können. Rotglühende Auswürflinge sind erst später gefördert worden, 19.5.15 wurde im Gipfelkrater ein zähflüssiger Pfropfen extrudiert. Auf- und absteigende Eruptionswolken lieferten im übrigen nur festes Material. Die erste paroxysmale Eruption am 14.6.14 ergab eine vertikale mit festem, durchweg nicht glühendem Material beladene Eruptionswolke, die sich 25 000 Fuss = 7620 m. über den Gipfel erhob, h =

[13] Arthur L. Day and E. T. Allen, "The Volcanic Activity and Hot Springs of Lassen Peak," *Carnegie Inst. Washington Pub. 360* (Washington, 1925).

TABELLE 7

MONT PELÉE 1902–5

h Datum	t_0	p_0	t_2	p_2	i_2	t_1	p_1	i_1	Bemerkungen
10 000 m.	70°	0.307	860°	62	2.650·	1000°	112	2.995·	Durchbruch, Staukuppe
5.5.02		At		At	10^{10} cal.		At	10^{10} cal.	
1 500 m.	95°	0.839	893°	141	2.776·	1039°	254	3.103·	Glutwolke im Gleichgewicht mit
16.12. 02		At		At	10^{10} cal.		At	10^{10} cal.	Felsnadel von 565 m. Höhe
2 500 m.	92°	0.749	680°	48	2.139·	823°	88	2.417·	Schlussexplosion
10.6. 05				At	10^{10} cal.		At	10^{10} cal.	

Höhenzuwachs Datum	Tagesförderung	log η	t_2	Bemerkungen
5–7.5. 02	$\sim 10^8$ cbm.	6.07613	860° 880°	Staukuppe
10 m. am Tage 24. 11. 02	$1.7671 \cdot 10^5$ cbm.	8.83978	700°	Felsnadel $r = 75$ m.
60 m. am Tage 3–12. 11. 02	$10.603 \cdot 10^5$ cbm.	8.06163	740°	Felsnadel
5 m. am Tage 13–18. 6. 05	$0.88355 \cdot 10^5$ cbm.	9.14081	680°	Kleine Felsnadel gegen Ende des Ausbruchs.

TABELLE 8

LASSEN PEAK 1914–15

h Datum	t_0	p_0	t_2	p_2	$\varkappa$	i_2	t_1	p_1	i_1	Bemerkungen
10 810 m.	68°	0.279	600°	16	1.28	$1.903 \cdot 10^{10}$	680°	29	$2.169 \cdot 10^{10}$	t_2 = Glutgrenze $\sim 600°$
14. 6. 14				At		cal.		At	cal.	Anfang der Eruption
12 334 m.	64°	0.233	756°	31	1.265	$2.355 \cdot 10^{10}$	854°	56	$2.667 \cdot 10^{10}$	Pfropfen, Höhepunkt
22. 5. 15.				At		cal.		At	cal.	Absteigende Wolken

10 810 m. über NN. Ein zweiter Paroxysmus am 22.5.15 erreichte h = 30 000 Fuss = 12 334 m. über NN. Der Lassen Peak–Pfropfen ähnelt dem Nautiluspfropfen auf Santorin, dessen Entstehungstemperatur zu 756° gefunden wurde. Die Temperatur des Lassen Peak lag zw. 600° und 756° und zwar oberhalb der Starrgrenze bei rund 740°. Mit diesen Daten erhält man die Zustandsgrössen in Tabelle 8.

TABELLE 9

	t_2	p_2	i_2	t_1	p_1	i_1	Morphol. Reihe	Temperatur gebiet
Sakura-jima.....	1048°	74 At	$3.375 \cdot 10^{10}$ cal.	1207°	133 At	$3.799 \cdot 10^{10}$ cal.	Strom-Staukuppe	1048°–800°
Santorin..	900°	127 At	$2.863 \cdot 10^{10}$ cal.	1041°	228 At	$3.221 \cdot 10^{10}$ cal.	Staukuppe-Strom-Pfropfen	900°–756°
Mont Pelé	893°	141 At	$2.746 \cdot 10^{10}$ cal.	1039°	254 At	$3.103 \cdot 10^{10}$ cal.	Staukuppe-Felsnadel	893°–600°
Lassen Peak...	756°	31 At	$2.355 \cdot 10^{10}$ cal.	854°	56 At	$2.667 \cdot 10^{10}$ cal.	Pfropfen-nicht glühender-Mat.	756°–600°

ZUSAMMENFASSUNG UND SCHLUSSFOLGERUNGEN

Die Zustandsgrössen, Temperatur und Spannung des Magmas an der Schlotmündung oder im Herde bestimmen die Art andesitischer Eruptionen und ihren Ablauf. Die morphologische Reihe Strom-Staukuppe-Felsnadel- festes Lockermaterial ist eine Reihe fallender Temperatur und zunehmender Viskosität. Im obigen ist der Versuch gemacht worden, diese Zustandsgrössen zahlenmässig zu bestimmen. In Tabelle 9 sollen die so gewonnenen Zustandsgrössen der vier andesitischen Vulkane Sakura-jima, Santorin, Mont Pelé, Lassen Peak nach fallender Intensität geordnet noch einmal gegenübergestellt werden.

PROPER NAMES, NOMENCLATURE, AND CLASSIFICATION

HAKON WADELL
University of Chicago

ABSTRACT

A review of current definitions of proper names is presented and a new definition is suggested. Examples of irrational, vernacular, and international nomenclature are constructively criticized. Nomenclature is shown to be intimately tied to the definition, the classification, and symbolic logic and logistic. Rules for progressive nomenclature are presented.

INTRODUCTION

If one should venture to estimate the amount of time which a student of geology devotes to memorizing geologic and geographic names and terms, it is probably safe to say that at least 50 per cent of the time spent on elementary courses in paleontology, stratigraphy, mineralogy, and petrography is given to nomenclature and terminology. Although attempts have been made in recent years to exercise the function Della Crusca in geological nomenclature and terminology, the tendency to excessive multiplication of nonuniform and irrational names and terms is still increasing. This condition is due to a variety of factors. The close relationship between nomenclature, definition, classification, and symbolic logic and logistic is seldom, if ever, adequately treated. The logicians have discussed the subject, voicing their dissatisfaction with the unchecked increase of irrational names proposed by many naturalists, but the criticism has received, with but few exceptions, slight attention, perhaps due to the usual difficulties in breaking with tradition and inherited learning. The fact that the number of names and terms for scientific use is steadily increasing with the development of science calls for a systematic treatment of scientific nomenclature. Librarians, in collaboration with logicians, have developed rational and progressive methods of cataloguing and classifying books, but the possibility of creating a similar efficient system in the natural sciences has received generally only slight attention. The fundamental distinction between proper names and common names is still an

open question, and this has been a contributing factor in preventing the development of a rational scientific nomenclature. In the present paper an attempt is made to elucidate the various problems involved, especially in regard to geological nomenclature in general.

DEFINITIONS OF PROPER NAME

The question, "What things have proper names?" was first raised in the year 1690 by John Locke,[1] who exemplified a *nomen proprium* by names of persons, countries, cities, rivers, and mountains. In 1875 John Stuart Mill[2] suggested that a proper name is "an unmeaning mark, which we connect in our minds with the idea of the object in order that, whenever the mark meets our eyes or occurs to our thoughts, we may think of that individual object." Proper names do not connote anything according to Mill, who illustrated a *nomen proprium* by the robber's chalk mark on Ali Baba's house, as described in the *Arabian Nights*.

Jevons[3] spoke of Mill's viewpoint as "probably erroneous." He argued that proper names have a way of reminding us of the facts we happen to know about their owners. "Surely no one who uses the name England, and knows what it denotes, can be ignorant of the peculiar qualities and circumstances of the country, and these form the connotation of the term." Sidgwick[4] objected to Jevons' criticism and said that Mill would never have wished to deny that proper names raise mental pictures. "If the only connotative names are descriptive names, then proper names (when used as such) are not connotative; on the other hand, if to connote is to excite ideas, then proper names, like all others, are connotative, and the whole value and meaning of the distinction is lost." Finally, Keynes[5] suggested that the controversy was merely verbal, the terms "connotation" and "connotative name" being used in different senses. He accepted Mill's idea and defined a proper name as follows: "A proper

[1] *Essay concerning Human Understanding*, Book III (1690), chap. iii, § 5.

[2] *System of Logic*, Vol. I (1875), pp. 36–37.

[3] W. Stanley Jevons, *Elementary Lessons in Logic* (1879), pp. 42–43.

[4] Alfred Sidgwick, *The Use of Words in Reasoning* (1901), pp. 246–47.

[5] John Neville Keynes, *Studies and Exercises in Formal Logic* (1906), pp. 13–14, 41–46.

name is a name assigned as a mark to distinguish an individual person or thing from others, without implying in its signification the possession by the individual in question of any specific attributes."

Gibson[6] says that a sign cannot be regarded as an unmeaning mark, and that the chalk mark in Mill's example meant the house of Ali Baba, and to this extent it signified the object to which it was attached. Mill and Gibson, however, are wrong in saying that the chalk mark signified the house of Ali Baba. It actually represented the house where Baba Mustapha had sewed up Kasim's corpse, the only fact known to the robber. A mark or a proper name of Mill's description cannot suggest anything more than that which our knowledge of the object includes. Svanberg[7] expresses a similar thought. When one says, "There comes Nils," it is assumed that Nils and the attribute which distinguishes him from Erik and Olof are known to the person to whom one speaks; in other words, that Nils is known in one respect or another. But proper names have that connotation in common with all others, as exemplified by saying, "There comes the man"; it must be assumed that the person to whom one speaks knows the man. And, although "man" in the English language implies the possession of a specific attribute by the person, from an objective viewpoint, it does not, however, characterize the person in question any more than the proper name "Nils."

Noreen[8] goes so far as to say that usually a proper name is not given for the purpose of expressing any characteristic feature of the object, but that it is perfect only when it is etymologically nontransparent, because then it characterizes the object as a whole and not in part. He calls the perfect proper names *fullblodsproprier*, i.e., "thoroughbred" proper names, a synonym of Sweet's "unconnected names." The latter author[9] divides proper names into "connected names" and "unconnected names," the former derived from common words in the same language, e.g., "Patience," "Violet," "Brown," and "Smith"; the latter exemplified by "Philip," "John," "London,"

[6] W. R. Boyce Gibson, *The Problem of Logic* (1908), p. 82.

[7] Nils Svanberg, "Studier i Språkets Teori," *Uppsala Universitets Årsskrift* (1930), p. 157.

[8] Adolf Noreen, *Vårt Språk*, Vol. V (1904), pp. 287–88.

[9] Henry Sweet, *A New English Grammar*, Vol. I (1892), pp. 56–61.

and "Thames." The following will show that neither Noreen's nor Sweet's reasoning is sufficiently sharp.

Germany has a river by the proper name Elbe which is etymologically identical with the Swedish common name *älv*, meaning river. To anyone unfamiliar with this fact, the name Elbe is an unmeaning mark, etymologically nontransparent and therefore an "unconnected" or "thoroughbred" name. Hence the question whether or not Elbe shall be classified as an unmeaning mark or an "unconnected name" depends on personal knowledge, which varies with the individual. A sharp objective demarcation between "connected" and "unconnected" names is therefore impossible.

Becker[10] said that "Die Eigennamen sind ursprünglich Gemeinnamen," and Sweet[11] claimed that the history of the language shows that "unconnected" names originally were "connected" ones. Others[12] believe that in ancient times the purpose of name-giving was not essentially identification or recognition but that the names were believed to possess magical power. Originally, however, the proper names were undoubtedly "connected" names as shown by the Hindu and Mohammedan personal names, for instance, *Cheta*, "born in the month of Chet"; *Kakkru*, "born in the cucumber season"; *Lulu*, "maimed"; *Magra*, "sulky"; *Mahomed*, "praised"; *Ali*, "exalted"; etc. Some "connected" names may have become disconnected in the sense that they are still etymologically transparent, but they have been attached later to objects which do not possess the attribute which suggested the name. In conclusion, it can be assumed a priori that the purpose and function of proper names have been practically the same in all times, whether or not they are "connected," "disconnected," or "unconnected"; and the fact that some proper names may have nondescriptive, etymologically nontransparent and unmeaning forms does not differentiate them from appellatives or common names, because many proper names are "connected" ones, and they have as much meaning as the common names. This fact disqualifies Mill's and Keynes's definitions which claim that

[10] K. F. Becker, *Ausführliche deutsche Grammatik*, Abt. I (1836), p. 225.

[11] *Loc. cit.*

[12] Anonymous, "Names," *Indian State Railwais Magazine*, Vol. X, No. 12 (1937), pp. 683–84.

a proper name is an unmeaning mark without any signification of any specific attribute of the object. Noreen's preference for an etymologically nontransparent name is invalidated by the same reasoning. It is obviously better to have a proper name which signifies one attribute by which the object can be recognized than nothing at all.

Noreen has analyzed several definitions of proper names. Michaelis'[13] definition: "Die Eigennamen bezeichnen Wesen (Personen und Sachen), die nur einmal vorhanden sind," is inadequate according to Noreen,[14] because names such as "Karl" and "Petersson" cannot occur *nur einmal*, and they are therefore disqualified as proper names. It is to be noted, however, that Michaelis meant to say that not the name which denotes the object but the object itself occurs *nur einmal*. Sütterlin's[15] expression: "Die Eigennamen, die nur einen bestimmten einzelnen Gegenstand benennen," and Heyse's:[16] "Propria, Eigennamen, Benennungen von Einzelwesen (Individua)," represent similar thoughts. Noreen said, however, that words such as "I" and "sun," each being an *Einzelwesen*, must accordingly be classified with the proper names, but that is not done in practice. Sweet[17] had previously said that "the fact that such a word as sun in popular language expresses only a single object does not make it a proper name, because in the word sun there is no intention of excluding other possible suns."

Noreen ends his analysis with the following definition: "A proper name is a word which is used purposely, and so far as possible without regard to the etymological connection, in order to distinguish a certain definite individual object from another (or other) individual object (or objects) in certain respects related."[18] The definition is invalidated by the arguments already presented against Mill and Keynes.

The preceding pages have shown that current definitions of a proper name are inadequate. A proper name can be almost anything from a simple mnemonic mark (Mill's chalk mark) to a phonetic and graphic picture in ideographic or alphabetic form. A number, an idiograph, or even a fingerprint may be regarded as a proper

[13] Noreen, *op. cit.*, p. 285.
[14] *Ibid.*
[15] *Ibid.*
[16] *Ibid.*, p. 284.
[17] *Op. cit.*, p. 58.
[18] *Op. cit.*, p. 287.

name when it is a unique identification mark of a unique thing. A new definition of a proper name is herewith suggested:

A proper name is a unique identification mark by which a unique thing is distinguished from other things in the same system of classification.

The fact that a proper name sometimes becomes a mark of universal identification value may be incidental or accidental. A proper name is primarily intended to be a unique identification mark of the object within the boundaries of that system of classification to which the object belongs, according to the object's definition based on such properties as are pertinent to the classification. An object, however, can have several names, one for each system of classification, but it can have only one name in one and the same system of classification. The fact that in practical life an object may be found to have more than one proper name in one and the same system of classification is due to bad organization and irrational nomenclature.

What is said in the preceding paragraph applies also to common names, but with some modifications. A common name may also be regarded as an identification mark, and, although it may well be unique, it does not signify a unique thing but is common to two or more things. A unique thing may be anything, concrete or abstract, which is thought of as a unique unit.

A general rule occurs in many languages that a common name is distinguished from a proper name by beginning the latter with a capital letter. Mentally, however, the two are not always so easily distinguished. In the phrase, "The King is dead, long live the King," the title "King" is intended as a proper name, as shown by the initial capital letter. The fact, however, that "King" signifies two different things, the dead king and the living king, would rank it with the common names, and therefore the initial capital letter is not justified. If "King" is regarded as an identification mark for both the living and the dead king, an ambiguity arises, which is undesirable but possibly permissible if dead kings and living kings belong to two different classifications, i.e., dead men and living men of a kingdom. In this manner "King" becomes a unique identification mark of a unique person in each system of classification. This reasoning was, of course, not in the mind of the person who invented the phrase,

but the case illustrates an undesirable but possibly permissible nomenclature.

It is to be noted that titles such as "Kaiser," "King," and "Queen" must be regarded as proper names when they are unique identification marks of a unique thing.[19] If the system of classification is expanded and the proper name thereby loses its identification value, additional identification marks must be added, resulting in binomial, trinomial, and polynomial proper names; for instance, "King George V of England." The title and place name are identification marks by which the identification value is increased to permit identification within a system of classification including all kings in the world.

IRRATIONAL NOMENCLATURE

Protests against the unchecked increase of irrational nomenclature have been voiced from time to time. Gibson says:

> We may feel considerable sympathy with Mr. Garden's protest against what he calls the evil fashion, once so prevalent amongst naturalists, of paying compliments by naming genera and species after each other. "What am I the better," he asks, "for hearing a rare moss called *Hedwigia hornschuchiana* beyond being led to infer that Germany has or had two botanists, one called Hedwig and the other Hornschuch?"[20]

Jevons[21] complained in the year 1901:

> The present nomenclature of igneous rocks is generally acknowledged to be unsatisfactory, for not only is it without useful meaning, but it is also so unsystematic that it forms a severe tax upon the memory. . . . . A new name is frequently invented, generally signifying nothing but the locality where the rock was first found, or the name of its discoverer.

Examples are abundant. A hypersthene-granite was found in southern India by Holland and was given the name Charnockite because the tombstone of Job Charnock, the founder of Calcutta, was made of this rock.[22] The proper name Charnockite is still an identification

[19] We have an analogy in the name God as distinct from "god," the former generally regarded as a proper name, i.e., a unique identification mark for a unique thing.

[20] *Op. cit.*, p. 68.

[21] W. Stanley Jevons, "A Systematic Nomenclature for Igneous Rocks," *Geol. Mag.*, Vol. VIII (1901), pp. 304–16.

[22] Albert Johannsen, *A Descriptive Petrography of the Igneous Rocks*, Vol. II (1932), pp. 234–35.

mark of the granite from the quarries of St. Thomé where the tombstone was cut, but the word has also become a common name, charnockite, for rocks of similar kind found elsewhere. It is inconvenient, if not incorrect, to convert a proper name Charnockite to a common name because the latter becomes a proper name Charnockite of the genus including all rocks commonly called charnockites. A definition *per genus et differentiam* of the Charnockite from St. Thomé reads, then: "A Charnockite is a Charnockite, etc.," which is vicious and ambiguous. Furthermore, "Charnockite" cannot excite any idea about the granite of St. Thomé, and it is absurd that Job Charnock is a characteristic feature or a part of the granite, and therefore his name should not be used as an identification mark of the rock.

In most cases it is illogical to name a rock after the locality where it first was found, for instance, Lindöite after Lindö, because Lindö cannot be a characteristic feature of Lindöite. It would be more appropriate to name the island after the rock. Finally, this nomenclature is not consistent for all rocks. If all rocks were named after localities, our petrographic nomenclature would look like an index of geographic names. The same criticism applies to stratigraphy, where the need of agreement in nomenclature is especially urgent by reason of the tendency to excessive multiplication of nonuniform stratigraphic names with the resulting confusion and burden on the memory.

A place name or toponym, however, may be imposed for practical purpose on a thing which is not topographic or geographic in character, when the intention is to preserve the identity of an object specifically related to the locality. Many commercial and industrial names are of this kind. For instance, "Carrara Marble" is a proper name given the marble quarried near Carrara in Italy, in order to distinguish this marble from others which have not gained the reputation of the Italian product. It is to be noted that we are concerned here with a trade classification, distinct in purpose from the petrographic one, and the two must be kept separated for several reasons. The petrographic nomenclature and classification is primarily intended for scientific use, while in trade nomenclature consideration must be given to a variety of factors which are not essential to the geologist. This fact, however, does not prevent the use of petro-

graphic names and terms in commercial publications, and conversely, trade names must frequently be adopted in textbooks of geology; but trade names should never be incorporated in the nomenclature based on the petrographic classification of rocks. Assimilation of trade and mining terms with geological terminology frequently leads to disputes as to the real meaning of the terms, and, since "practical" trade and mining terms usually have a popular and diffuse meaning, they should not be incorporated with geologic terminology when a sharply defined outline of the meaning is required.

An irrational nomenclature of peculiar kind is found in many geographic atlases. In English and American editions several non-English names are anglicized; for instance, "Steiermark" to "Styria"; "Kärnten" to "Carinthia"; "Böhmen" to "Bohemia"; "Schwarzwald" to "Black Forest," etc. In atlases of other countries the same peculiarity occurs, and names such as Rocky Mountains, Great Bear Lake, and Great Slave Lake are often translated into the editor's language. In other cases one notes impatiently, perhaps after hours of efforts to locate a minor place of specific interest by consulting several English and foreign atlases, that the spelling of a place name varies. For instance, the present-day Russian town Swerdlowsk has three additional names, Jekaterinburg, Ekaterinburg, and Katherinenburg. It is still worse when the traveler discovers that he cannot properly address a letter posted in one foreign country to another, a fact recently brought to attention by the librarian of the Royal Geographical Society in London.[23] Table 1 shows examples of the variation of the names Sweden and Germany in European languages in the Latin alphabetic form.

The name of a country used in another country is influenced by the structure and habit of the language. In this respect the proper names of the countries are not different from common names, a fact which shows that translated proper names are not true proper names, logically speaking, because they lose their universal identification value by translation. Proper names are primarily graphic identification marks, and their original and vernacular form should therefore be maintained, by general agreement, in the Latin alphabetic form,

[23] "The Names of Countries Used by Other Countries," *Geog. Jour.*, Vol. LXXXV (1935), pp. 458–62.

no matter in which language they are used. The pronunciation may be adjusted, however, for practical purposes, to suit each individual language. This viewpoint is well supported by comparison with personal names. Mr. Schuhmacher in Germany (Deutschland, to be correct) does not sign the name Shoemaker in letters addressed to English-speaking countries because his identity would be lost by translation.

TABLE 1*

Language	Germany	Sweden
French	Allemagne	Suède
Italian	Germania	Svezia
Spanish	Alemania	Suecia
Portuguese	Allemanha	Suecia
Romanian	Germania	Suedia
German	Deutschland	Schweden
Dutch	Duitschland	Zweden
Danish	Tyskland	Sverige
Norwegian	Tyskland	Sverige
Swedish	Tyskland	Sverige
Magyar	Németország	Svédország
Finnish	Saksa	Ruotsi
Estonian	Saksamaa	Rootsi
Latvian	Vacija	Zviedrija
Lithuanian	Vokietija	Švedija
Polish	Niemcy	Szwecja
Czech	Německo	Švédsko
Serbo-Croat	Nemačka	Svedska
Turkish	Almanya	Isveç

*Extracted from the table compiled by the librarian of the Royal Geographical Society.

In December, 1934, the Persian Ministry of Foreign Affairs addressed a circular memorandum to the foreign diplomatic missions in Tehran asking that the terms "Iran" and "Iranian" might be used in official correspondence and conversation instead of "Persia" and "Persian" hitherto used. It is hoped that other countries will follow suit and demand that each shall be known by its strictly official vernacular name.

The "evil fashion," so prevalent among explorers, of paying compliments by introducing personal names in geographic nomenclature, has affected especially the nomenclature of the polar regions, which gives the impression of a social register of explorers and patrons of science and their relatives. Nomenclature of this kind is historically

rather than geographically orienting. It is worth noting that older toponyms of this kind usually render difficulties to historical-toponymic interpretation because of the etymological development and the original lack of connection between the name and the topographic features of the object.

With the decline of Latin as the universal language of science, scientific nomenclature and terminology which had not already been established in Latin form became gradually a conglomeration of names and terms derived from several languages. Some terms, retaining their vernacular form, are meaningless to anyone who does not know the original meaning of the word, while other terms have been translated into several languages, resulting in a multiple nomenclature of synonymous words. In the latter case it has not always been possible to obtain an adequate translation due to idiomatic variations of the languages. For instance, the Swedish term *varvig* has been used in the geological literature both in vernacular and in translated form. The English translation "laminated" (clay) does not convey the entire meaning of *varvig*, the latter connoting something of cyclic nature.

Names and terms of vague and indefinite meaning always reflect upon a subject inexactness and an "it-is-believed" tendency of opinion. If a vernacular name is raised to the rank of scientific nomenclature without being properly defined, it retains that hazy and multiple meaning so common to all words used in everyday language. Failing to investigate the etymology and previous use of the word often leads to disputes as to priority and original meaning. The application of a name to a thing which has been poorly described often raises the question whether or not the same name can be used as designation for other things which are essentially the same but still differ in some respects, however unimportant to the definition and classification. Definitions based on both concrete and abstract distinctions frequently lead to confusion because abstract distinctions are often hypothetic and consequently subject to changes. The name of an object with certain concrete and abstract characteristics cannot be applied to another object with the same concrete properties but with different abstract qualities unless the latter are disregarded.

The nomenclature of glacial geology is full of irregularities and faults of the kind described in the preceding paragraph. A single brief example, however, may serve as an illustration. That type of ridge which is commonly known in the English language by the name "esker" has in the past been described in geological literature under more than a score of vernacular names. In general, the same type of ridge is meant, but the names are not entirely synonymous, owing to the fact that each name has often been applied originally to a ridge specimen described in respect to details which are not common to all eskers. In this manner the name signifies a specimen, and the critical worker is unable to apply the same name to other ridges which have fundamentally the same properties but which differ in nonessential details. It is important that the first proposer of a new name gives a definition *per genus et differentiam* of the object for which the name is proposed. A description is far from being always a definition, since the former usually carries unessential details. In an early stage of research it may be difficult to propose a valid definition, owing to the fact that the essential features cannot be differentiated, and this fact must be kept in mind by subsequent workers in order to avoid confusion. The fact that the esker problem is still unsolved is in part due to the fact that an esker has never been properly defined.

The first scientific description of Swedish *åsar* (eskers) was given by Emanuel Swedenborg[24] in the year 1719. He noted their shape and general trend and described the composition of the *ås* material and the roundness of the stones. W. J. Sollas[25] in 1896 said that he was unable to admit priority of the word *ås* without further information. He claimed priority for the Irish "esker" on the basis of O'Donovan's translation of the *Annals of the Four Masters* of A.D. 123, where Esker Riada is mentioned as a line of gravel hills extending from Dublin to Clarinbridge in the county of Galway, Ireland. Priority on such grounds is not justified because the Swedish *ås* is

[24] "Om Watnets Höjd och Förra Werldens starcka Ebb och Flod bewjs utur Swergie" (1719), *Opera quaedam aut inedita aut obsoleta de rebus naturalibus* (Regiae Academiae Scientiarum Suecicae, Vol. I [1907]).

[25] "A Map To Show the Distribution of Eskers in Ireland," *Scien. Trans. Royal Dublin Soc.*, 2d ser., Vol. V (1893–96), pp. 785–822.

probably, etymologically speaking, as old as the Irish esker, and, above all, priority starts with the first introduction of the name in scientific nomenclature. In 1891 Chamberlin stated correctly that the Scandinavian *åsar* is entitled to precedence because the ridges by this name first received notable attention in Scandinavia.[26] He said, however, that the word "esker" is coming to be used by many American writers somewhat freely as a synonym and is preferred by some for phonetic reasons. The Swedish *ås* is still used, however, in various corrupted forms for phonetic reasons; for instance, in English ose, plural oses; in America, also, osar, plural osars; in French *oesar;* in German *Os*, plural *Oser*, or *Osar*, and less common *Åsrücken*, and *Åsarrücken* (tautology). *Längsåsar*,[27] *Grandrücken*,[28] *Wallberge*,[29] and even *Radialmoränen*[30] have been used more or less as synonyms of the Swedish *ås* in geological publications in the German language. In the English language we find that Page in 1865, Maxwell Close in 1867, Lyell in 1873, A. C. Ramsay in 1872, Penck in 1894, and many other authors have used the words "kame" and "esker" as synonymous.[31] In 1912 the British Geological Survey followed the same course.[32] Other more or less synonymous terms are "Indian ridges," "hog ridges," "kame ridges," "continuous kame," "serpent kames," "linear moraines,"[33] etc.

[26] T. C. Chamberlin, "A Genetic Classification of Pleistocene Deposits," *Compte-rendu of the Fifth Session of the International Congress of Geologists* (Washington, 1891), pp. 116–92.

[27] Emil Werth, "Studien zur glazialen Bodengestaltung in den skandinavischen Ländern," *Zeitschrift Gesellschaft f. Erdkunde zu Berlin* (1907), p. 90.

[28] Felix Wahnschaffe, "Über einen Grandrücken bei Lubasz," *Jahrbuch der Königl. Preussischen geologischen Landesanstalt und Bergakademie zu Berlin*, Vol. XI (1890), pp. 277–88.

[29] M. Schmidt, "Über Wallberge auf Blatt Naugard," *Jahrbuch Königl. Preussischen geologischen Landesanstalt und Bergakademie*, Vol. XXI (1900), pp. 81–82.

[30] Emil Werth, "Über einige Radialmoränen (Åsar) südlich von Posen und ihre Beziehungen zu den radialen Rinnenseen," *Zeitschrift f. Erdkunde zu Berlin* (1909), pp. 540–46.

[31] J. W. Gregory, "The Relations of Kames and Eskers," *Geog. Jour.*, Vol. XL (1912), pp. 169–75.

[32] *Ibid.*

[33] Edward Hitchcock, "The Phenomena of Drift, or Glacial-Aqueous Action in North America, between the Tertiary and Alluvial Periods," *Reports of the First, Second,*

Multiple nomenclature of the kind exemplified above leads to confusion, and especially because some writers have eliminated the majority of the names and retained only a few without presenting valid reasons for such action. It is still worse when all ridges of the kind are indiscriminately classified under the term "glacio-fluvial deposits" in connection with an abstract genetic classification. There are as many hypotheses for the origin of these ridges as the number of names by which they are known. Before an abstract genetic classification is possible, the nomenclature and classification based on qualitative and quantitative methods must first be established.

NOMENCLATURE IN RELATION TO DEFINITION AND CLASSIFICATION

In order to accomplish a rational nomenclature, the things to be named must be defined and classified on the basis of such properties and distinctions as are pertinent to the classification, to the purpose of use, and to the class of people for whom the nomenclature is primarily designed.

A definition is "die elementärste unter den systematischen Formen, weil Klassifikation und Beweisführung auf ihr weiterbauen."[34] The definition of a thing gives the name's defined connotation, which is needed in constructing the meaning of the name. Usually a thing is defined *per genus et differentiam*, i.e., the definition mentions the genus of the thing and a minimum number of distinctive marks by which the thing is separated from other things of the same genus. The term "genus" is used in logical rather than biological sense, and a "genus" as used in a definition may be equal in rank to a subspecies, a species, a genus, an order, or a class of the biological classification. The rank of the logical genus depends on the rank of the thing which is to be defined and on the structure of the classification.

Many bi-, tri-, and polynomial rational names are in themselves definitions of a kind. In Linné's well-known nomenclature the first name is the generic one, followed by one, two, or more specific terms. His genus *Arena* has six species, the first of which is defined by the

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and Third Meetings of the Association of American Geologists and Naturalists (1840–42), pp. 164–221.

[34] Wilhelm Wundt, *Logik*, Vol. II (1907), p. 40.

polynomial name *Arena riparia s. qvartzosa, inaeqvalis.*[35] The sand is defined by the genus *Arena* followed by specific toponymic and qualitative terms. The sequence of the terms is the same as that which is generally found in definitions, i.e., from the genus to specific details. The reverse sequence, however, is commonly used in sedimentographic nomenclature, e.g., "ferruginate siliceous conglomerate," "calcarinate calcareous sandstone," and other similar names recently proposed by Wentworth.[36] The latter is governed by the custom of the language of placing the adjectives before the noun. The sequence followed by Linné is, however, probably the most rational one, although, owing to tradition and custom of speech, it seems somewhat awkward when applied to the English language. A thing is found usually by restricting the limits gradually from the larger unit to smaller ones, i.e., the sequence generally followed in name constructions by Linné. A blind adherence to this rule, however, is not recommended, and adjustments should be made to fit the classification, the nomenclature, and eventually other factors of importance.

Names and terms of the kind exemplified above are common in current sedimentographic nomenclature, which, however, lacks the foundation of a rational and logically developed classification, resulting in an incomplete, truncated, and inconsistent nomenclature. The names are often descriptive and no great burden to the memory, but they are unduly long in proportion to the material knowledge conveyed, a disadvantage which it is difficult to avoid when words instead of symbols are used. The terms express qualities only, which, in an effective sedimentographic nomenclature, must be complemented with quantitative terms expressing definite numerical values.

Classification is the sorting and grouping of things according to established rules governed by the purpose of the classification and the nature of the things. "Broad classification" involves an arrange-

[35] Carl Benedicks, *Linnés Pluto Svecicus och Beskrifning öfwer Stenriket* (1907), p. 79. *Pluto Svecicus* was written by Linné in 1734.

[36] C. K. Wentworth, "Principles of Compound Nomenclature," *Report of the Committee on Sedimentation* (Washington, D.C.: National Research Council, 1935–36), pp. 42–43.

ment of things in classes, divisions, or sections. "Close classification" is an arrangement of things in minute divisions as under a class or division, followed by any degree of division required. A "flexible classification" is one which will allow of intercalation of a new thing without destroying the sequence or logic of arrangement. The nomenclatures based on the three types of classifications are termed broad, close, and flexible, respectively,[37] and the same terms are applied to the names of the respective nomenclatures. A complete and rational nomenclature is a broad, close, and flexible combination of almost any degree of variation, by which the names can be constructed to express anything from the largest features to the minute details of the classified things without infringing upon the rules of the classification and nomenclature. The resulting nomenclature may be called an *elastic rational nomenclature*. The term "elastic" implies that the number of terms or symbols composing a name can be reduced or increased to suit the purpose of expression. A flexible name, on the other hand, is one which will allow of intercalation of a new term or symbol, or of expansion of already existing ones to include in its signification new properties and to permit the development of the "romance" of the next decimal, respectively.

Geology is unfortunate in the respect that the things pertinent to the subject are difficult to arrange into a single well-constructed and complete classification, owing to the great number of complex factors involved. There are three elements to be considered, each designated by a symbol as follows:

P = Position in space
Q = Quality
T = Time and chronological sequence

Each element can be expressed in three ways: (1) in definite numerical values related to a definite base and scale, (2) in numerical sequence related to a definite base but to a numerical scale of indefinite values, and (3) in terms related to a nonfixed base and a nonfixed scale. The first may be illustrated by expressing the position of a point with reference to geographical co-ordinates and alti-

[37] The terms, "broad, close, and flexible classification" have been adopted from the librarians' book classification (M. Mann, *Introduction to Cataloguing and the Classification of Books* [1930], pp. 45–47).

tude above sea-level. The second, by expressing the position of a point by a number with reference to a numerical sequence from a fixed place, but without implying by the number any exact numerical distance. The third, by expressing the position by terms such as "beach," "river," "plain," "slope," "abyssal," "plutonic," "extrusive," etc. The three ways are termed in the following, the *first*, the *second*, and the *third degree of exactness*, respectively.

A classification and nomenclature which include all three elements may be called a PQT-classification and a PQT-nomenclature, respectively. The aim of all scientific organization is to attain a PQT-classification and nomenclature of the first degree of exactness.

NOMENCLATURE IN RELATION TO SYMBOLIC LOGIC AND LOGISTIC

Symbolic logic began with Leibnitz and was further developed by DeMorgan, Boole, Jevons, Peirce, MacColl, Schröder, Whitehead, and others. Lewis[38] defines Symbolic Logic as follows: "Symbolic Logic is the development of the most general principles of rational procedure, in ideographic symbols, and in a form which exhibits the connection of these principles one with another." He makes distinction between symbolic logic and "logistic," the latter defined as "the science which deals with types of order as such." Logistic is rather a method than a subject and

> may be taken to denote any development of scientific matter which is expressed exclusively in ideographic language and uses predominantly (in ideal cases, exclusively) the operations of symbolic logic.[39] . . . . The logistic method is applicable wherever a body of fact or theory approaches that completeness and systematic character which belongs to mathematical systems. And by the use of it, the same assurance of correctness which belongs to mathematical portions of scientific subjects may be secured for those portions which are not stateable in terms of ordinary mathematics.[40]

The conditions of valid reasoning, by the aid of symbols, are given by Boole[41] as follows:

[38] C. I. Lewis, *A Survey of Symbolic Logic* ("Semicentennial Publications of the University of California" [1918]), p. 1.

[39] *Ibid.*, p. 340.

[40] *Ibid.*, p. 371.

[41] Philip E. B. Jourdain, *George Boole's Collected Logical Works*, Vol. II (1916), p. 74 (George Boole, *The Laws of Thought* [1854]).

1st, That a fixed interpretation be assigned to the symbols employed in the expression of the data; and that the laws of the combination of those symbols be correctly determined from that interpretation.

2nd, That the formal processes of solution or demonstration be conducted throughout in obedience to all the laws determined above, without regard to the question of the interpretability of the particular results obtained.

3rd, That the final result be interpretable in form, and that it be actually interpreted in accordance with that system of interpretation which has been employed in the expression of the data.

Generally, the simplest form of symbolic logic and logistic methods is used in construction of nomenclature because the mnemonic element is considered to be of prime importance, and a name must be easy to read, write, and remember. The name in its best form is a single "shorthand" expression akin to a mathematical formula, combining in a logical manner the symbols and figures representing or expressing the facts and forces in a natural sequence pertinent to the classification. Figures must be used in nomenclature of the first degree of exactness, and both letters and figures may be used as symbols. Opinions vary as to whether letters or figures are the easier to remember, and Bacon[42] says that every practical system sooner or later makes use of both letters and figures. Richardson[43] recommends notations "which will allow for indefinite subdivision, using mixed symbols, but with a predominant decimal base." Different types of letters may be used as symbols for different things, as, for instance, on maps where physiographic and political names usually are distinguished by different types. When figures express definite quantitative values, they must either be arranged in a definite significant sequence or else attached to a symbolic prefix, subprefix, surprefix, or, more commonly, to a subindex signifying the thing expressed by the figures. In this connection it is interesting to note how tenaciously the sedimentographic nomenclature has been maintained in popular terms, such as "gravel," "coarse sand," "medium sand," "silt," "clay," etc. This nomenclature lacks exactness, elasticity, and flexibility and is a constant burden on the memory because the limits of the grain sizes established for each term must be remembered in order to use the words properly. A numerical expres-

[42] C. Bacon, *Classification* (1925), p. 7.

[43] E. C. Richardson, *Classification, Theoretical and Practical* (1912), pp. 42–43.

sion does not occupy more space than one composed of letters, and the former has the advantage of imparting to the mind directly the exact size value. For instance, "Q,0.1–0.5," signifying a quartz sand of a grain size from 0.1 to 0.5 mm., occupies less space and is easier to remember than, for instance, Sherzer's[44] terminology according to which the same thing is termed "very fine to coarse sand." For the use of terms such as "Q,0.15–0.58" the student has to memorize only that "Q" is the symbol for quartz and that the subsequent figures represent the grain-size limits of a sediment. In Sherzer's terminology the whole range of class limits from clay to gravel must be memorized in order to use the terms properly, and, furthermore, the exactness of expression is limited to the size of the classes.

RATIONAL NOMENCLATURE

Rational nomenclature is best achieved with the help of a survey chart of classification, accompanied by a "nomenclature key," which explains the rules of combination and the fixed interpretation assigned to the symbols. A rational nomenclature of the highest order is the PQT-nomenclature of the first degree of exactness, which is based on definitions and classification founded on definite quantitative values adequately expressed by figures and symbols, with a predominant decimal base permitting expressions of any degree of exactness required.

A rational nomenclature of the highest order hitherto achieved in geology is that of igneous rocks proposed by Johannsen.[45] It is mainly a Q-nomenclature of the first degree of exactness, with, however, three genetic P-elements of the third degree, i.e., plutonite (P), extrusive (E), and hypabyssal (H). Definitions and classification are strictly mineralogical, quantitative, and modal. The classification is arranged as a double tetrahedron, of which each trihedral angle represents certain mineral components. The nomenclature key is based on the classification and on definite rules for combining the symbols according to computations of definite quantitative values of the mineral classification. The names are composed of three numerical

[44] W. H. Sherzer, "Criteria for the Recognition of the Various Types of Sand Grains," *Bull. Geol. Soc. Amer.*, Vol. XXI, pp. 625–62.

[45] *Op. cit.*, Vol. I.

symbols, arranged according to Linné's system of sequence, the first symbol representing the highest rank or the class, the second the order, and the third the family. The P-elements mentioned above are represented by letter symbols following the numerical symbols. The flexibility of the numerical nomenclature is limited, but this condition is compensated by a verbal nomenclature by which also the breach with the traditional petrographic nomenclature appears to be less radical. The classification and nomenclature proposed by Johannsen is an example of a rational procedure of organization which may serve as a guide for a future reorganization of all geological nomenclature.

RULES FOR PROGRESSIVE NOMENCLATURE

The term "progressive nomenclature" implies that the names involved are built on a rational and progressive base, which adequately corresponds to the stage of exactness of the scientific subject for which the nomenclature is designed. It is obvious that all nomenclature cannot be a PQT-nomenclature of the first degree of exactness, because all elements (P, Q, T) are not always needed, nor can they always be expressed in definite numerical values, owing to the fact that all branches of science have not reached the development of exact qualitative and quantitative methods. The following general rules are intended to serve as a guide for progressive nomenclature.

1. Determine the educational level of the class of people for whom the nomenclature is primarily designed. The mnemonic element is of prime importance, and the names and terms must be easy to read, write, and remember. When a great number of names are involved, however, the mnemonic efficiency of the entire nomenclature is of greater importance than the assistance which an effective individual name construction may render the memory.

2. In order that the nomenclature shall be effective in purpose, the efficiency and exactness must be sacrificed sometimes in practical life for psychological, aesthetic, and material values, but in scientific nomenclature the former must always be the guiding factors.

3. Determine the field for which the nomenclature is primarily designed, e.g., geology, physics, botany, industry, aviation, com-

merce, etc. The nomenclature must fill its purpose within the specified sphere of interest, but consideration should also be given to related fields. Several names for one and the same thing, one name in each field or subject, should be avoided when the properties pertinent to the classifications have the same magnitude of interest in each field. Unfortunately, a thing is often found to have one name in geology, another in physics, a third in engineering, etc. The nomenclature of that branch of science to which the thing is primarily related should be given first consideration.

4. Classify the various things on the basis of properties pertinent to the interest and construct a survey chart of classification.

5. Define each thing *per genus et differentiam* on the basis of distinctive properties and their sequence of importance in the classification.

6. Draft a nomenclature key on the basis of classification and possible combinations of properties and apply the rules of symbolic logic and logistic, with the importance of the mnemonic elements, however, always in mind.

7. Give each name such form that the thing is defined by the meaning, expressed either in verbal form or by symbols in a significant arrangement based on the classification. Linné's system of sequence from genus to specific distinctions is generally the best. Bi-, tri-, and polynomial names are justified when definition and clear meaning require additional terms.

8. Consideration should be given to national and international application. For an international nomenclature a combination of letter and number symbols is to be preferred because it does not need to be translated, whereas verbal names often lead to a multiple nomenclature composed of inadequately translated names. Vernacular names of nonuniversal languages should be avoided. Vernacular names should not be translated but maintained in their vernacular graphic form, by general agreement in letters of the Latin alphabet. If a vernacular name is raised to the rank of scientific nomenclature, the meaning must be defined, as it otherwise retains that hazy and multiple meaning so common to all words used in everyday language.

9. A name must be as concise, flexible, and elastic as possible, and preferably constructed on a decimal base.

10. A proper name in verbal form is indicated by an initial capital letter. Proper names should never be translated. A name composed of one or more symbols may often be regarded either as a common name or as a proper name, the latter recognized by its capacity of being a unique identification mark of a unique thing.

11. Investigate the original meaning and the etymological derivation of all words intended for scientific names and terms. Instead of adopting already existing words of hazy and multiple meanings acquired through the etymological development, it is often better to construct an entirely new name of defined meaning, thereby avoiding any complications which may arise from words of multiple and popular meanings.

12. The graphic form in Latin letters must adequately express the vernacular phonetic form. Violation of this rule especially affects many toponyms which show evidence of deficient phonetic grasp of the surveyer and cartographer.

13. Avoid names of phonetic similarity, e.g., Schmidt, Smidt, Smitt, Smyth, etc.

14. Avoid "unconnected" and "thoroughbred" proper names and all metaphoric names.

15. Philologists often condemn etymological hybrids, i.e., words derived from two languages, e.g., sociology, glaciology, sedimentology, stratigraphy, terminology, and other similar names. Etymological hybrids, however, are common in all modern languages, and their adoption in scientific nomenclature and terminology can no longer be regarded as an offense. The logic must be satisfied in the first place.[46]

16. If a thing has been lost through generations and it is again discovered, the discoverer has the right to name his findings.

17. In the choice between an older and a younger name, the former has the right of precedence if meaning and connotation of the two are identical. If, however, any doubt exists in respect to the connection between the older name and the thing in question, a new

[46] Hakon Wadell, "Sedimentation and Sedimentology," *Science*, Vol. LXXVII, No. 2005 (1933), pp. 536–37.

name is justified on the grounds that it is better to have two names for one and the same thing than one and the same name for two things.

18. In science priority belongs to that name which was introduced first in scientific nomenclature.

19. In suggesting new proper names, especially geographic and place names, it is advisable to submit the proposition to the authorities, political or others, for approval. Many countries maintain a permanent committee on geographical names.

20. Finally, for the construction of rational names and terms one must not only be acquainted with the rules and elements of progressive nomenclature but a thorough knowledge is needed with respect to the character, properties, origin, and development of the things pertinent to the subject for which the nomenclature is designed.

In conclusion, the alarming increase of irrational names and terms applied to many branches of science calls for a radical change. The development of bibliographic and chemical nomenclatures into well-organized, efficient, and time-saving mnemonic devices has shown itself of use in the advancement of science. The present paper is an attempt to promote the interests of improving geological nomenclature in general, and to serve as a guide in the construction and selection of names and terms for scientific use.